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Improving Real Estate Management and Environmental Building Performance through IT Systems and Dynamic Data

Esmir Maslesa

PhD dissertation

DTU Management Engineering

In collaboration with KMD

May 2019

Preface

This dissertation forms part of an industrial PhD project conducted in collaboration between the Danish IT company KMD and the Technical University of Denmark (DTU). The project has been carried out by industrial PhD fellow Esmir Maslesa at KMD and DTU's Department of Management Engineering.

Main supervisor:	Per Anker Jensen
Co-supervisor:	Morten Birkved
Company supervisor:	Jannik Hultén
Project period:	February 2016 – January 2019
Funding:	KMD
	Innovation Fund Denmark (grant no. 5016-00174B)

In loving memory of my Bosnian ancestors, and for my descendants.

Sa dragim sjećanjem na moje bosanske korijene, i za moje potomke.

English summary

A strategic approach and holistic planning are important elements of sustainable building development. They can be supported by current technology, which, for example, can visualise and benchmark a building's actual environmental performance. However, management of environmental building performance (EBP) through IT systems has experienced difficulties in gaining a solid base, partly due to a lack of core data on buildings, but also to erroneous consumption data and a lack of any overview of consumption patterns.

This PhD dissertation shows how the implementation of certain IT systems in Real Estate Management (REM), including Facilities Management (FM), can promote sustainability by reducing REM's negative environmental impacts. This is primarily achieved through the successful implementation of IT systems that can process large amounts of different data on buildings and their performance. However, to succeed with the implementation, IT systems must support the business processes that an organisation requires regarding REM or FM.

Nowadays IT systems such as Integrated Workplace Management System (IWMS) and Energy Management System (EMS) can collect, combine, analyse and present core data and dynamic consumption data. This opens up new possibilities to base EBP on actual operating data and provides opportunities for deeper performance analysis and faster failure detections. As at the time of writing research-based knowledge about IWMS is relatively limited, this PhD has chosen to study what this system actually is, how it can be implemented, what benefits it can realise and how the system, in combination with EMS, can be used to improve EBP. The research focus has been on four different REM/FM organisations that use various IT systems to monitor and benchmark EBP. The empirical results from the main case study show that IWMS implementations are complex and require a lot of resources, though they can add value particularly to large-scale REM organisations. In addition, the three remaining case studies show that the EMS is particularly beneficial for collecting and processing dynamic data on electricity, heating and water consumption. Moreover, the research shows that EMS can be further supported by BMS (Building Management System), which focuses on the management of technical installations, and that even simple IT systems like Microsoft Excel can be used to report and benchmark EBP. Cross-case analysis shows that in practice the focus in IT systems is on energy and water consumption and emissions, while environmental categories regarding space management, building materials and recycling are either not supported in IT systems or are not used by the organisations studied.

The PhD project also studies the future potential for managing and benchmarking EBP through IT systems. In dynamic life-cycle modelling and analysis of high-resolution data, the research shows that EBP not only depends on the energy consumption, but also on the time of that consumption and the location of the building (region).

Finally, based on empirical observations and research results, this PhD proposes a step-by-step model for improving EPB through IT systems.

Dansk resumé

Strategisk tilgang og helhedsorienteret planlægning er vigtige elementer i en bæredygtig bygningsudvikling. Disse elementer kan understøttes af nutidens teknologi som for eksempel kan vise bygningernes aktuelle miljøperformance, samt benchmarke deres indbyrdes performance. Benchmarking af bygningernes miljøperformance i IT-systemer har dog haft vanskeligheder ved at få solidt fodfæste, delvis på grund af manglende stamdata omkring bygninger, men også på grund af misvisende forbrugsdata og manglende overblik på forbrugsmønstre.

Denne ph.d. afhandling viser hvordan implementeringen af bestemte IT-systemer i ejendomsforvaltningen kan fremme bæredygtighed ved at reducere de negative miljømæssige konsekvenser af ejendomsdrift. Dette sker først og fremmest ved succesfuld implementering af IT-systemer, der kan håndtere store mængder af forskelligartet data omkring bygninger og deres performance. Samtidig skal IT-systemerne understøtte de forretningsgange som organisationen efterspørger ifm. ejendomsforvaltningen/Facilities Management (FM).

I dag findes der IT-systemer som Integrated Workplace Management System (IWMS) og Energy Management System (EMS), som kan opsamle, kombinere, analysere og præsentere stamdata og dynamiske forbrugsdata. Dermed åbnes nye muligheder for at basere bygningernes miljøperformance på faktiske driftsdata med muligheder for dybere performance analyser og hurtigere fejlrapportering. I skrivende stund er forskningsbaseret viden omkring IWMS relativt begrænset, og denne ph.d. har derfor som udgangspunkt valgt at studere hvad dette system faktisk er, hvordan det kan implementeres, hvilke gevinster det kan realisere, samt hvordan systemet i samspil med EMS kan bruges til at forbedre bygningernes miljøperformance. Forskningsfokus har været på fire forskellige ejendomsorganisationer/FM organisationer, som hver på egen måde bruger diverse IT-systemer til at monitorere og benchmarke bygningernes miljøperformance. De empiriske resultater fra hoved casestudiet viser, at IWMS implementeringer er komplekse og kræver mange ressourcer, men at de især kan tilføje merværdi til store ejendomsforvalterorganisationer. Desuden viser de tre øvrige casestudier, at EMS er særlig fordelagtig for indsamling og bearbejdning af dynamiske data for el-, varme- og vandforbrug. Ph.d. forskningen viser også at EMS kan supporteres af CTS (Central Tilstandskontrol og Styring), som fokuserer på styring af de bygningstekniske anlæg, og at simple IT-systemer som Microsoft Excel også kan bruges til at adressere bygningernes miljøperformance. Tværgående case analyse viser, at fokus i IT-systemer i praksis er på energi- og vandforbrug og emissioner, mens miljøkategorier vedr. arealforvaltning, bygningsmaterialer og genanvendelse enten ikke understøttes i IT-systemer, eller ikke er i brug i de studerede organisationer.

Ph.d. projektet undersøger også fremtidige potentialer for håndtering og benchmarking af miljø-performance gennem IT-systemer. Ved dynamisk livscyklus modellering og analyse af højopløsningsdata viser forskningen at bygningernes miljøperformance ikke alene afhænger af energiforbruget, men også af forbrugstidspunktet, og bygningens beliggenhed (landsdel).

Afslutningsvist, på baggrund af empiriske observationer og forskningsresultater foreslår denne ph.d. afhandling en trinvis model for optimering af bygningernes miljøperformance gennem IT-systemer.

Acknowledgements

The initial ideas for this industrial PhD started to flourish at the end of 2014, when as a research assistant I first met Martin Dam Magnussen, KMD's then Business Line Manager, at the research Centre for Facilities Management (CFM) at DTU. Martin explained how KMD was starting a new business area within IT in Facilities Management (FM). KMD was interested in an industrial PhD collaboration with CFM to examine and document how an Integrated Workplace Management System (IWMS) could be deployed and developed within an FM context in Denmark.

Together with Susanne Balslev Nielsen, Associate Professor and Deputy Head of CFM at that time, we agreed on collaboration and submitted a project proposal for the industrial PhD project. The application was finally approved in December 2015. I am truly grateful to Martin and Susanne, who believed in this project from the beginning and gave me the chance to combine research and practice in the best way possible through this industrial PhD.

My PhD journey started in February 2016, with Susanne as my main supervisor. In January 2017 Susanne took a new job position outside of DTU, and Associate Professor Per Anker Jensen was appointed as my main supervisor in her stead. I had the pleasure of collaborating with Per previously, while I was a research assistant, and I was pleased to be working with him again. Per has been a great support during the PhD, providing a lot of valuable input and feedback on research ideas, academic publications, study plans and research dissemination. I felt privileged having Per as my main supervisor, and I sincerely thank him for his guidance during the project.

I would also like to thank Morten Birkved, my university co-supervisor, and Jannik Hultén, my company supervisor, who both followed the PhD throughout and provided useful input from different perspectives to this research. I really learned a lot about Life Cycle Assessment from Morten, and about Business Development and IT implementations from Jannik and his competent KMD Atrium team. My thanks also go to Simon Bolwig of the Systems Analysis division at DTU, who co-supervised the project for a year and a half before becoming Head of Division. Simon provided constructive criticisms and interesting perspectives on the topic, which I incorporated into my research subsequently.

During the PhD, I benefited from an external research visit to Anglia Ruskin University in Chelmsford and Cambridge, United Kingdom. I thank Professor Keith Jones for enabling this visit and introducing me to their research environment. Special thanks also go to Carlos Jimenez-Bescos for his kindness and guidance during the visit, and for providing contacts for the case study.

I also thank my brilliant colleagues at DTU Management Engineering (Helle, Asger, Jakob and Supuck) and in the KMD Atrium team (Jakob, Ilona, Magnus, Erika and Beatrix) for a pleasant working environment, valuable inputs and feedback, and for many informal knowledge-sharing sessions.

I am grateful for the support from my family, above all my dear wife Vildana and our lovely son Ajdin. They made a lot of sacrifices and showed great support during the PhD, especially during our residence in Odense, while I was spending many days far away from home. Thank you for being a wonderful family!

DTU, May 2019
Esmir Maslesa

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Abbreviations

API	Application Programming Interface
ARU	Anglia Ruskin University
BMS	Building Management System (in Danish: CTS)
BPR	Business Process Reengineering
BRM	Benefit Realisation Management
BYGST	Bygningsstyrelsen (Danish Building and Property Agency)
CAFM	Computer Aided Facilities Management
CMMS	Computerised Maintenance Management System
CREM	Corporate Real Estate Management
CSR	Corporate Social Responsibility
DFM	Danish Facilities Management Association
EBP	Environmental Building Performance
EMS	Energy Management System
ERP	Enterprise Resource Planning
FM	Facilities Management
GHG	Greenhouse gas
HVAC	Heating, Ventilation, Air Conditioning system
ICG	Implement Consulting Group
IEQ	Indoor Environmental Quality
IT	Information Technology
IWMS	Integrated Workplace Management System
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
O&M	Operation and Maintenance
PREM	Public Real Estate Management
REM	Real Estate Management
ROI	Return on Investment
SLR	Systematic Literature Review

1. INTRODUCTION

The evolution of Real Estate Management (REM), including Facilities Management (FM), over time can be attributed to several important factors from three thematic groupings: I) business environment, including organisational structure, business objectives, and company culture and contextual issues; II) characteristics of buildings and facilities, for example, facility type, location and size; and III) external interventions and factors, such as business needs and processes, asset maintenance priorities, legislation and relationships with other contractors (Pärn et al., 2017). Accurate, reliable and ubiquitous information is therefore vital for supporting efficient REM. However, the REM sector continues to struggle with information management, mostly due to the peculiarity of the relevant information and its fragmentation (Eastman et al., 2008; Pärn et al., 2017). Thus, IT systems are needed to manage the data and information necessary to make decisions about how to operate and maintain buildings (Lewis et al., 2010).

According to earlier research (Ebbesen, 2016), IT systems and technologies in REM and FM can be grouped into seven categories, as illustrated in Figure 1: data and information repositories, interoperability standards and protocols, workflow systems, facilities intelligence systems, sensor and mobile systems, field data-capture systems and communication systems.

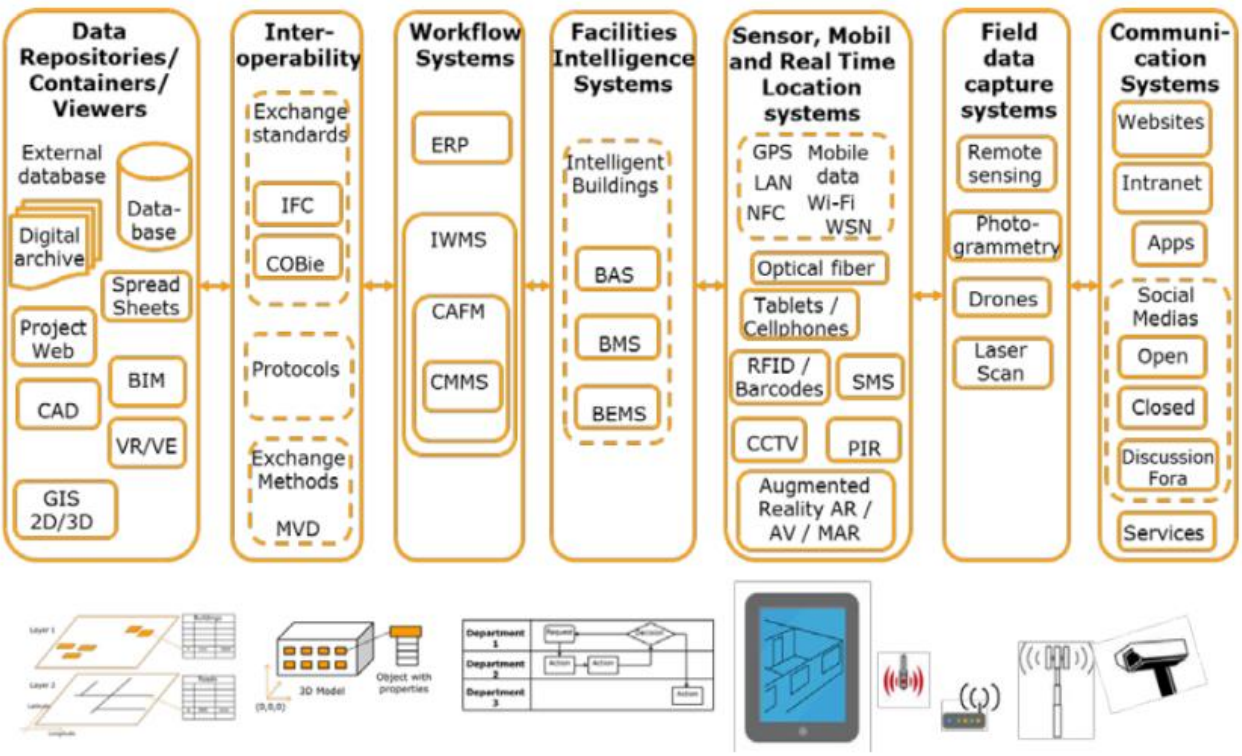

Figure 1: IT in FM (Ebbesen, 2016).

In Denmark, the focus seems to be mostly on workflow systems such as Computer Aided Facilities Management (CAFM) and Integrated Workplace Management Systems (IWMS). In recent years the Danish FM Association (DFM) has published annual reports on FM systems and identified at least fifteen different workflow systems on the Danish FM market, of which six are CAFM systems and four are IWMS solutions, while the remaining five systems have diverse definitions (Computerised Maintenance Management System/CMMS, service management solution, resource optimisation system (ROS), FM system, and Property Management system) (DFM, 2018). System functionality and complexity depend on the type of system selected.

There are four major IT system types within the Danish FM and REM sector: ticket management systems, CMMS, CAFM and IWMS (DFM, 2018). Figure 2 shows the system types, their interrelationships and system complexities.

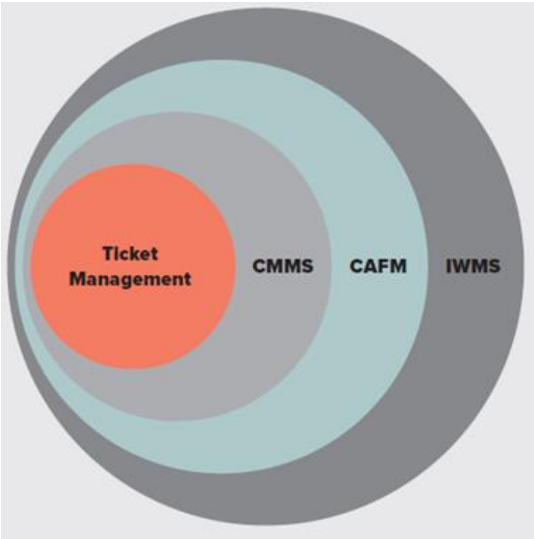

Figure 2: Major IT system types in the Danish FM sector and their system complexity (DFM, 2018).

Ticket management systems are considered to be simple FM systems whose core function is to respond to and resolve FM-related enquiries received by email. A ticket management system is usually part of the customer support department, but it may also take the form of an IT supporting function. CMMS focuses on building maintenance and specialises in planned maintenance, including planning, documentation and work registration. CAFM is considered to be an advanced form of CMMS and can typically manage planned and reactive maintenance, as well as other functions like room bookings and resource management. IWMS is perceived as the most complex FM system, since it includes all functionalities from CMMS and CAFM and offers additional modules like finance, portfolio management, lease management and space management.

In 2014, the Danish IT company KMD started a new business area on FM systems in strategic collaboration with the software developing company Trimble (formerly the Manhattan Software Group) of London, UK. As a result of this collaboration, KMD now offers the IWMS solution “KMD Atrium” (globally known as “Manhattan”), which REM and FM organisations can use for various tasks within portfolio management. IWMS contains many cross-functions, such as those between business economics, maintenance tasks, land use, leases, relocation management, energy management, etc., but many of these options are not yet fully integrated into REM organisations. In 2016 KMD also acquired EMT Nordic, a software developing company specialising in energy and environmental management. Due to this acquisition, KMD now also provides an Energy Management System (EMS) called "KMD EnergyKey" on the market. "KMD EnergyKey" specializes in reporting and monitoring energy consumption data from the built environment.

Through case studies and interaction with KMD's customers, this industrial PhD contributes with new knowledge from REM and FM practice about the strengths and weaknesses of IT systems IWMS and EMS. Moreover, it also aims to reveal how REM and FM organisations can use IT systems to improve their business processes by better utilisation of building core data and performance data.

Commercially the PhD project aims to disclose the benefits of the "KMD Atrium" and "KMD EnergyKey" IT systems for potential customers, especially within the public real estate sector.

While commercial reasons for conducting this industrial PhD focus on IT systems, including their implementation drivers, process, and benefits within the REM and FM sector, the scientific drivers aim to research and contribute new knowledge within environmental sustainability in the built environment. Nowadays many terms are used in attempts to communicate the fact that some buildings are performing better than others when it comes to their environmental sustainability. For example, we meet sustainable buildings, green buildings, certified buildings, smart buildings etc., and yet the statistics show that the buildings and building construction sector combined consume 36% of global energy consumption and produce nearly 40% of total CO_2 emissions (IEA, 2017). Furthermore, a deeper look at buildings' environmental performances from a life-cycle perspective shows that the use stage of older buildings is typically responsible for 80-90% of environmental impacts, while newer, more "sustainable" buildings have lower operational impacts at the expense of higher embodied impacts. This development indicates that there are burden-shifting tendencies between life-cycle stages, as has been covered in research several times (Sharma et al., 2011; Cabeza et al., 2014; Nielsen et al., 2016).

Assessing sustainability in buildings is not an easy task and must include all three dimensions (economic, environmental and social) of sustainability. However, this PhD particularly focuses on the environmental aspects of sustainability and therefore uses the term "environmental building performance" (EBP) to address environmental impacts induced during a building's operation and maintenance activities.

Building performance assessment has focus on the behaviour of a building under actual conditions of operation. Building performance assessment is seen as a mean to ensure that a building and its parts meets specific building requirements, and so determine the 'building quality' according to specific assessment criteria (Maslesa et al., 2018). In this PhD, environmental building performance (EBP) focuses particularly on environmental impacts from buildings during their "active" service life, i.e. during the use stage.

1.1. State of the Art regarding IT systems in REM/FM

Several studies have earlier addressed IT in real estate management and facilities managemen and the findings indicate narrow and limited research within the research field of IT systems in REM and FM. In the following, state of the art regarding IT systems in REM and FM is presented, highlighting what is already researched in the field, where the knowledge gaps are, and what new knowledge the PhD provides.

A decade ago, Elmualim and Pelumi-Johnson (2009) studied the use of computer aided FM systems for intelligent buildings and noted that computer aided FM systems contribute to the business of facilities management and organisations. Benefits included the advantages of sharing data with other departments, faster processing time, cost savings, reduced crisis management, reduced errors, reduced personnel, better control of information, increased product quality, and helping to avoid penalty clauses. However, at that point, the integrated (strategic) facilities management had not found its way to the market yet and there was no true integrated FM system.

Ebbesen (2015) conducted a literature study on information technology (IT) in facilities management and found that IT in general is in the early stages of diffusion in FM organisations. Moreover, the literature study showed that 75% of studied articles had focus on conceptualisation and development, while only 25% focused on implementation and use in organisations, indicating an unbalanced research focus. The study concluded that much new knowledge could be gained by studying FM organisations, where technologies are being implemented and used, as this knowledge could be fed back into and strengthen conceptualisation and development of IT, thereby adding more value to FM.

Lewis et al. (2010) examined how to operate and maintain high performance buildings through technologies, processes and skills. They found that there are many new tehcnologies that facilities managers are not familiar with, and they pointed out that it is often challenging to find the time and/or resources necessary to understand the benefits of technologies, how they work, and the costs of implementing them. Lewis et al. (2010) identified and described several IT systems for managing high performance buildings, and noted that successful implementation of some advanced systems (e.g. CAFM, IWMS) can be challenging due to a lack of understanding of the importance of accurate asset inventories and maintenance records. However, they argued that a common user interface and integration are key parts of high-performance building software, because they support system-thinking and increase the synthesis between people, processes and technologies used in buildings. Furthermore, they highlighted the necessity for transition from commonly used silo-thinking to system-thinking as high performance buildings cannot be operated or maintained without considering both the impact of decisions on the entire organisation and the impact on the technical systems in buildings. System-thinking must be applied to building systems and to organisational processes related to maintenance management, user training and strategic planning, e.g. workplace management. Even though Lewis et al. (2010) addressed many relevant issues important for managing environmental building performance, their research lacked specific cases on IT implementations, their drivers, befenefits, and impacts on EBP.

Gibler et al. (2010) evaluated corporate real estate decision support software solutions and noted that a wide range of software tools is now available, making the choices more complicated and time consuming. They identified eight important parameters for software selection (business processes, referrals, scalability, interoperability, platforms, IT outsourcing, costs, and vendor viability) and compared point solutions with IWMS. Gibler et al. (2010) found that IWMS implementations tended to be more comprehensive, were more difficult, and cost more than the more specialised, point solutions. More recently, Hanley and Brake (2016) studied how IWMS can help organisations to transform real estate management and provided several key benefits from supporting cases. They argued that real estate management organisations face challenges relating to the complexity and variability of the data that they can manage, and in line with Lewis et al. (2010) pointed out that, REM data historically has been managed in siloed systems and departments, lacking consistency. Hanley and Brake (2016) also claimed that IWMS could be used for transition from silo-thinking to system-thinking as IWMS uses the same underlying data set whether performing maintenance tasks, scheduling projects, or disposing of an asset. Moreover, Hanley and Brake (2016) identified several critical success factors in implementing IWMS and highlighted some general benefits of using IWMS, but they lacked focus on IWMS drivers and environmental building performance.

Even though we live in a digital age in which data and IT systems can provide valuable insights on our buildings and their performance, there is still limited knowledge on IT in FM, especially regarding IT system IWMS and its benefits for REM/FM organisations. For example, the results from Ebbesen's literature study (2015) highlighted the need for more research of IT implementations in FM organisations as this could strengthen conceptualisation and development of IT, and thereby add more value to FM. Hanley and Brake (2016) provided a highly valuable study of IWMS and listed several benefits of IWMS in different organisations, but their research did not cover the implementation process. Lewis et al. (2010) argued for system-thinking but lacked concrete examples of the benefits of system-thinking approach.

Thus, this PhD dissertation provides new knowledge regarding IT in REM and FM though case studies of IT implementations and compares the findings with earlier research identified in state of the art. The PhD study focuses particularly on the relationship between IT systems and data and environmental building performance as there is a missing research link between digitisation and environmental sustainability. Moreover, the PhD examines the system-thinking approach through specific case studies of IWMS implementation, to determine the pros and cons of system-thinking, when compared with silo-thinking approach.

2. RESEARCH DESIGN

2.1. Research questions

The state of the art indicates limited research on IT in REM and FM and advocates for more case studies within this research field to highlight the benefits of digitisation in this sector. The literature covered in previous section lacks a more comprehensive focus on IT system types IWMS and EMS, and, more importantly, on the management of environmental building performance (EBP) through IT systems. The lack of research within this field has motivated this PhD project to examine the following research question:

How can IT systems and dynamic data support improving environmental building performance, and thereby also real estate management?

To answer the research question, four sub-questions were formulated in order to break down the work and ensure a more strategic approach to the research:

RQ1 What performance indicators are necessary and sufficient to provide an adequate expression of the EBP during building operation and maintenance?

RQ2 What dynamic data are available from KMD's customers using IT systems IWMS and EMS, and how can they be applied to the EBP indicators identified in the first research question? Are there any gaps between theoretical EBP indicators and the EBP indicators that IWMS and EMS use in practice?

RQ3 How does IWMS and EMS implementation support real estate management? Is there a difference in implementation drivers between public and corporate REM organisations, and between larger and smaller organisations? What are the customers' needs for dynamic data, and how capable are IWMS and EMS in supporting them?

RQ4 What are the benefits of IWMS and EMS implementation for environmental building performance, and thereby also real estate management?

Each sub-question is answered through one or more academic publication(s). Table 1 shows the research methods used in answering the specific sub-questions and in which publications the answers can be found.

Research question	Research method used	Answered in academic publication	Paper no.
RQ1	Systematic literature review (SLR)	*Indicators for quantifying environmental building performance: a systematic literature review.* (Maslesa, Jensen and Birkved, 2018) *10 questions concerning sustainable building renovation.* (Jensen, Maslesa, Berg and Thuesen, 2018)	*P1* *P2*
RQ2	Case study	*The implementation impacts of IT systems on energy management in real estate organisations.* (Maslesa and Jensen, 2018)	*P3*
RQ3	Case study	*Drivers for IWMS in real estate management.* (Maslesa and Jensen, 2019a)	*P4*
RQ4	Case studies Quantitative data analysis and LCA modelling	*Managing environmental building performance through IT systems.* (Maslesa and Jensen, 2019b) *Environmental performance assessment of the use stage of buildings using dynamic high-resolution energy consumption and data on grid composition.* (Karl, Maslesa and Birkved, 2019)	*P5* *P6*

Table 1: Publications overview and their relationship to sub-questions.

The main research question is answered by synthesising the results in the model development in Section 5.5 and by summarising the answers to the four sub-questions in the Conclusion (Chapter 7) to this thesis.

Besides the publications in Table 1, several other publications have been published during the PhD research. The complete publication list in chronological order is provided in Appendix C.

2.2. Research scope and limitations

This research was conducted in close collaboration with practice. The collaboration with KMD enabled easier access to cases and research data, as well as work in the field (e.g. studying IT implementation), thus bringing more practical relevance into the research.

The research focus was on specific IT systems and their features, particularly regarding environmental sustainability. Figure 3 shows IT systems studied in this PhD.

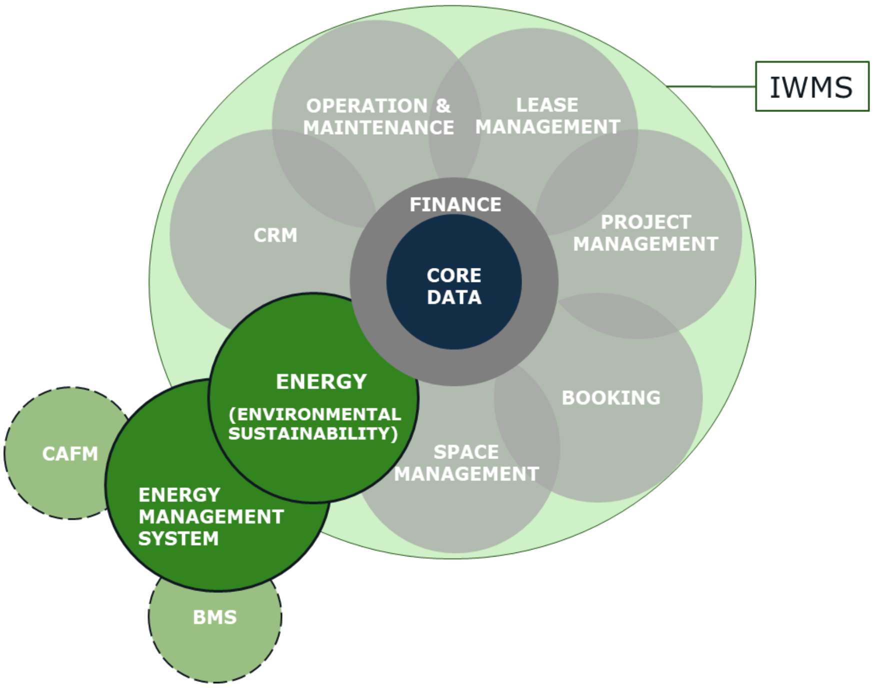

Figure 3: Research scope in the PhD project.
The focus is on environmental sustainability features in selected IT systems.

The focus was primarily on IT systems provided by KMD. The IT systems studied were (in prioritised order):

1. Integrated Workplace Management System (IWMS) “KMD Atrium” and its energy module
2. Energy Management System (EMS) “KMD EnergyKey”
3. IT systems BMS and CAFM (not provided by KMD, but related to EMS)

The author had personal, in-depth access to KMD’s IWMS and EMS products and was therefore able to study these systems from software provider perspective. On the other hand, case studies of REM and FM organisations provided customer perspective and expectations of the systems, ensuring more balanced picture of the customer-supplier relationship.

The research findings are practice-oriented and have certain limitations. Most case studies (3/4) were conducted in Denmark and thus within Danish real estate management and facilities management context. Since the research project was conducted for an industrial PhD, all three Danish cases were related to KMD. In the first case (BYGST), KMD provided IWMS and EMS solutions. The second case was KMD’s own facilities management department, and in the third case (Postnord DK) KMD’s EMS solution was used. The fourth case was conducted in the United Kingdom (UK) as part of an external research visit intended to compare Danish and UK IT system solutions.

2.3. Methodology

The selection of research methods is influenced by the methodology chosen (Gray, 2009). The methodological approach to answering the research question in this PhD is presented with reference to the Research Onion Model proposed by Saunders et al. (2016). Figure 4 shows the Research Onion Model and highlights the research approach adopted. Research data from multiple sources were used and analysed in answering the research question. The methodological choice was a multi-method qualitative study since it allowed studies of the various effects of IT systems in REM and FM organisations. Many of these effects were difficult to measure quantitatively except for the study of dynamic data in which a mono-method quantitative approach was applied to data analysis. Qualitative research data can lead to more valuable findings and help researchers go beyond their normal conceptions to generate other conceptual frameworks (Miles et al., 2014). Most research data were collected through document studies, field observations and semi-structured interviews based on open-ended, process-oriented questions. The principal strategy was case-study research, supported by action research and archival research. Action research strategy was considered particularly appropriate in the first case since the researcher at one point took part in the actual implementation. As such, the researcher was involved in changing an organisational environment through IT implementation.

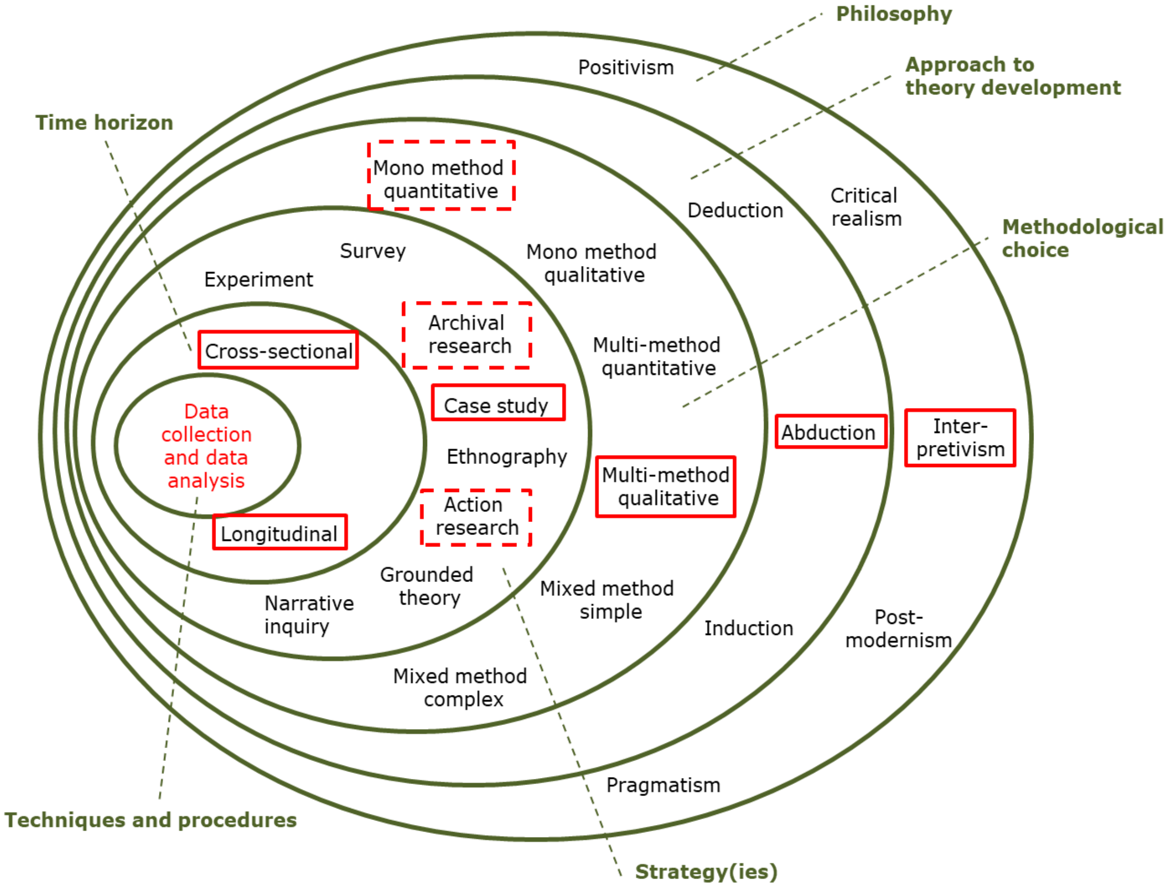

Figure 4: The Research Onion Model. The research approach and methods are highlighted in red (based on Saunders et al., 2016).

The empirical work included four case studies, of which one was an in-depth longitudinal case study and three were minor case studies. For purposes of generalisation, the cases were selected carefully rather than being of sufficient size. The selected cases were four contrasting organisations (Yin, 2014): the in-depth study was of a large public REM organisation with more than 4 million m^2 in its building portfolio; the second case study was of a relatively smaller private company with a building portfolio of approximately 105,000 m^2; the third case study was of a national postal company with approximately 600,000 m^2 in its building portfolio; and the last case study was of an educational institution in the UK that managed 119,000 m^2 of educational buildings. By studying these contrasting cases, the project aimed to reveal the needs of different organisations on EBP and REM/FM tasks in IT systems.

In case studies, the research data were collected through interviews, document studies, field observations and participation in implementation meetings and workshops. The different data sources were used to provide important background and contextual material for the research. However, when working with qualitative data, the potential for observational bias must be assessed. The simultaneous strength and weakness of qualitative data is their reliance on the use of a "human instrument" in participant observation (Robson and McCartan, 2015). Thus, several issues like data reliability, different forms of bias (interviewer bias, response/interviewee bias, participation bias), cultural differences, generalisability and validity/ credibility of results needed to be considered during data collection and analysis (Saunders et al., 2016).

This PhD used abduction as its overall research approach, a method used in many case study-based research processes (Alvesson and Sköldberg, 2009). Abduction starts from an empirical basis, but does not reject theoretical preconceptions like induction, being in that respect closer to deduction. In abduction a single case is interpreted from a conceptual framework, which, if true, explains the case in question. The interpretation is later strengthened by new cases. Abduction is not a simple mix of inductive and deductive approaches and cannot be reduced to either of these since it adds new, specific elements. During the research process, the empirical area of application is successively developed, and the theory (the proposed over-arching pattern) is adjusted and refined.

Abduction is particularly applicable in case-study research, because the main difficulty of case studies is handling the interrelatedness of various elements in the research work (Dubois and Gadde, 2002). Dubois and Gadde (2002) found that, by constantly going back and forth from one type of research activity to another, as well as between empirical observations and theory, the researcher could broaden his or her understanding of both theory and empirical phenomena. As such, the abductive approach was considered most suitable for this PhD as the research strategy was to collect data to study a phenomenon (how IT systems can improve EBP), identify themes and patterns, locate them in a conceptual framework and test its validity. The research context was the natural setting of users of IT systems to establish trust, participation, access to meanings and in-depth understanding regarding IT implementation processes in REM/FM organisations and the impacts IT systems can have on environmental building performance.

Three types of research assumption are made in distinguishing research philosophies: ontology, epistemology and axiology (Saunders et al., 2016). Ontology refers to assumptions about the nature of reality. Epistemology concerns assumptions about knowledge, what it is, and how it can be communicated to others. Axiology covers the role of values and ethics within the research process. Moreover, the business and management research philosophies are scattered along a multidimensional set of continua between two opposing extremes: objectivism and subjectivism. This PhD applied a subjectivist viewpoint for studying different organisations and their IT systems. Subjectivism claims that social reality is created from the perceptions and consequent actions of people. Ontologically, social constructionism is considered appropriate, since it claims that reality is constructed through social interaction in which actors create partially shared meanings and realities. Since social interactions are a continual process, it is necessary for a researcher to study a situation in detail, including its historical, geographical and socio-cultural contexts, to understand what is happening and how realities are being experienced. The subjectivist researcher is interested in different opinions and narratives capable of accounting for the different social realities of different social actors.

Another dimension of differentiation between research philosophies relates to the researcher's political or ideological orientation towards the social world being investigated. Saunders et al. (2016) have introduced a 2x2 matrix of four distinct and rival paradigms of organisational analysis. The matrix in Figure 5 shows the four paradigms and how they relate to research perspectives (regulation, radical change) and subjectivism and objectivism.

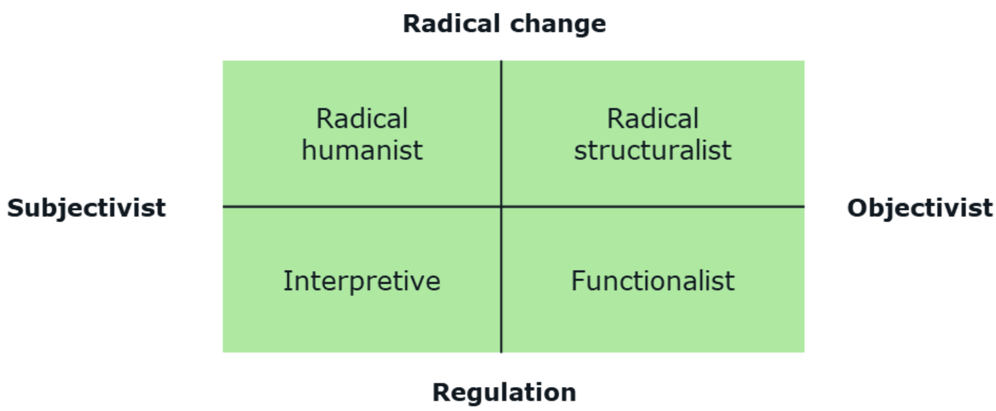

Figure 5: Four paradigms for organisational analysis (Saunders et al., 2016, p. 133).

The interpretivist perspective is highly appropriate in the case of business and management research, including for this PhD. An interpretive approach was used for understanding how IT systems impact environmental building performance and real estate management in different organisations, given the lack of research-based knowledge within this field. In interpretivism, the researcher attempts to understand phenomena by accessing the social world of his or her research participants and understanding that world from their point of view. Interpretivism seeks relativistic, albeit shared understandings of the phenomena in order to understand the deeper structure of a phenomenon, which can later be used to inform other settings (Rowlands, 2005). Interpretive research does not predefine dependent or independent variables and does not set out hypotheses, but instead aims to produce understandings of the social context of the phenomenon in question and the process whereby the phenomenon influences and is influenced by the social context (Walsham, 1995). In interpretivism, the primary focus of research is to understand the fundamental meanings attached to organisational life (Saunders et al., 2016). The aim is to become involved in the organisation's everyday activities in order to understand and explain what is going on, rather than to change things. Interpretivism is explicitly subjectivist, as it focuses on complexity, multiple interpretations and meaning-making. In this PhD, business situations in studied organisations were in many cases complex and unique in terms of context, arguing for an interpretive philosophical approach.

2.4. Data collection and research approach

In accordance with the multi-method qualitative study approach, several scientific methods have been used in collecting the necessary research data. Figure 6 illustrates the research approach for data collection and analysis. The following sections provide detailed descriptions of the research approach.

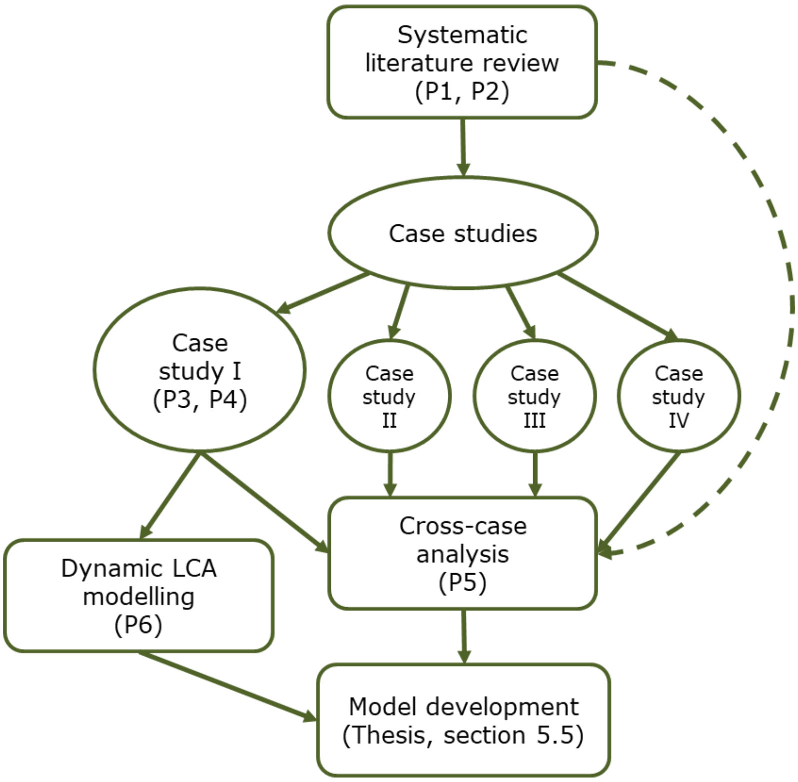

Figure 6: Research approach for data collection and analysis.

2.4.1. Systematic literature review (P1, P2)

To determine necessary and sufficient performance indicators for environmental building performance, and show how they can be quantified, from March to September 2016 a systematic literature review (SLR) was conducted according to the criteria presented in Okoli and Schabram (2010). The SLR presented in P1 included four stages with eight underlying steps: planning stage (purpose and protocol), selection stage (literature search and screening), extraction stage (quality appraisal and data extraction) and execution stage (analysis and findings, and writing the review). An SLR was chosen as research method for analysing the body of knowledge and identifying potential research gaps. The literature was reviewed to identify the main environmental indicator categories and their role in relation to the whole life-cycle of buildings. In the literature review, only journal papers published from 2010 onwards were considered.

Besides the SLR of papers quantifying environmental building performance, the author co-authored publication P2 on sustainable building renovations as a part of the PhD, briefly highlighting the topics that also might have relevance for EBP. P2 showed which tools can be used for target setting and evaluation of building renovations (Section 2.7) and explained how sustainability targets can be measured in building renovations (Section 2.8).

2.4.2. Case studies (P3, P4)

After determining the main environmental categories from the SLR, case studies were conducted. Case studies had the goal of examining which of the previously identified EBP categories were used in IT systems in practice, and for what reason(s). Furthermore, the case studies were used to reveal different organisations' needs regarding EBP and real estate management and to assess how well IT systems could support their needs. The research methods used in the case studies built on previous work by Yin (2014) and Miles et al. (2014).

Four organisations were studied: the Danish Building and Property Agency (Bygningsstyrelsen/BYGST), the private IT company KMD, the national postal company Postnord Denmark, and the educational institution Anglia Ruskin University in the United Kingdom. The selected organisations had maximum variations and contrasts (Flyvbjerg, 2006), since they were of different organisational types (governmental, private and public, educational), while building portfolio size also differed (between 105,000 and 4 million m^2). Each case was therefore initially treated as an independent study, and later compared in the cross-case analysis.

BYGST was the main case studied, the three other organisations being considered supporting cases. The study of BYGST was a longitudinal study in which the phenomenon (the impact of IT implementation on EBP) was studied over time. The longitudinal study observed organisational changes and developments relating to the IWMS and EMS IT systems over the three-year period (2016-2018). Moreover, BYGST was defined as a REM organisation, while the three remaining cases were considered to be FM organisations. The difference between REM and FM organisations is described in Section 3.1.

The research findings from the main case study resulted in two academic publications (P3 and P4). P3 revealed the implementation impacts of IWMS and EMS on energy management at BYGST, while P4 examined drivers for IWMS implementation in real estate management.

The primary data source for the case studies was semi-structured interviews. In total, ten interviews were conducted, five with BYGST, two with KMD, two with Anglia Ruskin University and one with Postnord Denmark. Interviews were based on open and closed interview questions prepared in advance and outlined in an interview guide. The interview sessions were prepared according to the guidelines provided by Kvale and Brinkmann (2015). The same interview guide was used for all interview sessions, allowing easier comparison of the results between the interviewees, both within and across the different organisations. The interview guide had fixed themes, while the interview questions were more flexible and could change slightly during the interview session, depending on progress with the interview. Table 2 provides more details on each interview session.

Case study	Interviewee	Business area	Interview date	Interview duration
BYGST	IT senior consultant	Project management, IT Change management	19-05-2017	01:30:49
	Technical consultant	Energy management	06-06-2017	0:53:34
	Head of IT dept.	IT systems and data	16-08-2017	0:56:56
	Head of Building dept.	Operation and maintenance Construction projects	18-08-2017	1:18:43
	Head of Lease dept.	Lease management	03-10-2017	00:53:14
KMD	Head of FM dept.	Facilities management Hard FM	14-09-2017	0:48:34
	FM director	Facilities management Hard and soft FM	31-10-2017	1:00:13
Postnord Denmark	FM specialist	Operation and maintenance Facilities management	07-11-2017	1:02:35
Anglia Ruskin University	Sustainability engineer	Operation and maintenance Building Management System (BAS)	10-04-2018	1:48:59
	Environmental manager	Environmental sustainability CSR reporting	17-04-2018	0:43:54

Table 2: Overview of interviews.

Besides interviews as the primary data source, secondary data sources, namely document studies and field observations, were used for collecting additional research data. Document studies were used in all four cases to provide background information on different organisations and their IT systems, possibly including documents on organisational history, core business, building portfolios and systems design for different IT solutions.

Since BYGST was the main research case, more comprehensive, in-depth document studies and field observations were applied during the IWMS/EMS implementation process (2016-2018) to collect additional research data. In-depth document studies covered for example High-Level and Low-Level system design documents and Project Initiation Document (PID). Field observations included participation in six implementation meetings, four workshops and seven observation days on-site for a better understanding of the decision-making process and customer expectations on IWMS. Implementation meetings covered internal KMD meetings and meetings between KMD and BYGST's energy specialists on energy management design solutions. Workshops covered team sessions, including representatives from all organisations involved in implementing the IWMS. On-site observations were personal observations at BYGST's headquarters. During the sessions, the researcher made personal notes and took pictures, to document the implementation process, and use the material as a part of research data. Besides formal interview sessions and field observations stated above, many hours at BYGST were spent on informal meetings, conversations and knowledge-sharing sessions related to the implementation of IWMS. The informal inputs are used as supplementary background data as appropriate.

2.4.3. Cross-case analysis (P5)

After data collection for each case, cross-case analysis was performed in P5. The cross-case analysis was conducted to determine similarities and differences between the organisations studied regarding EBP and their needs for IT systems. Moreover, in the analysis, empirical results from case studies were compared with research findings from P1 to determine, how many environmental categories from P1 were used in practice and assess the ability of different IT systems to manage data on environmental categories from P1. Furthermore, the cross-case analysis revealed the existence of two IT models for managing EBP.

2.4.4. Dynamic LCA modelling (P6)

To examine the future potentials of IT systems and dynamic data, an in-depth study of high-resolution energy data from BYGST was conducted. This study is presented in P6. The research was based on hourly data sets from 2017 on the national electricity grid composition and building-specific electricity consumption data for eighteen office buildings in Denmark. National electricity grid data were provided by Energinet, Denmark's national transmission system operator for electricity and natural gas. The data were supplemented by additional data on energy production in Denmark from the Danish Energy Agency. The goal of using supplementary data was to increase the resolution of the data for both local and central power production. BYGST provided specific electricity consumption data for eighteen state-owned office buildings, matching the data format and resolution of the electricity grid data. The eighteen office buildings selected for the study were equally distributed between eastern and western Denmark, with nine buildings in each part of the country. Once the high-resolution (hourly) data for electricity production and consumption was available, a Life-cycle Assessment (LCA) approach was used to quantify the environmental impacts of electricity consumption in office buildings and the importance of data resolution. The quantitative data analysis and LCA modelling were performed using open LCA software by a Master's thesis student, Asger Alexander Wendt Karl, whom the author of this dissertation was co-supervising.

2.4.5. Model development

Based on the findings from the cross-case analysis and LCA modelling, this PhD dissertation proposes a new EBP model in Chapter 5 (Findings) showing how EBP can be improved by using IT systems and dynamic data. The model is inspired by the research and advisory company Gartner's view of the future potential of EMS, adapted and developed in accordance with the results of this PhD research. Gartner is specialised in technology research and has published several reports and market guides on IWMS, EMS, and other industrial IT platforms.

3. THEORETICAL BACKGROUND

Based on the scope of the research, three research fields were identified as relevant for the case studies and were combined to answer the research question: Real Estate Management (REM), IT and Environmental Building Performance (EBP). Figure 7 shows how these research fields relate to each other and which specific theories and topics from each research field were used in this research.

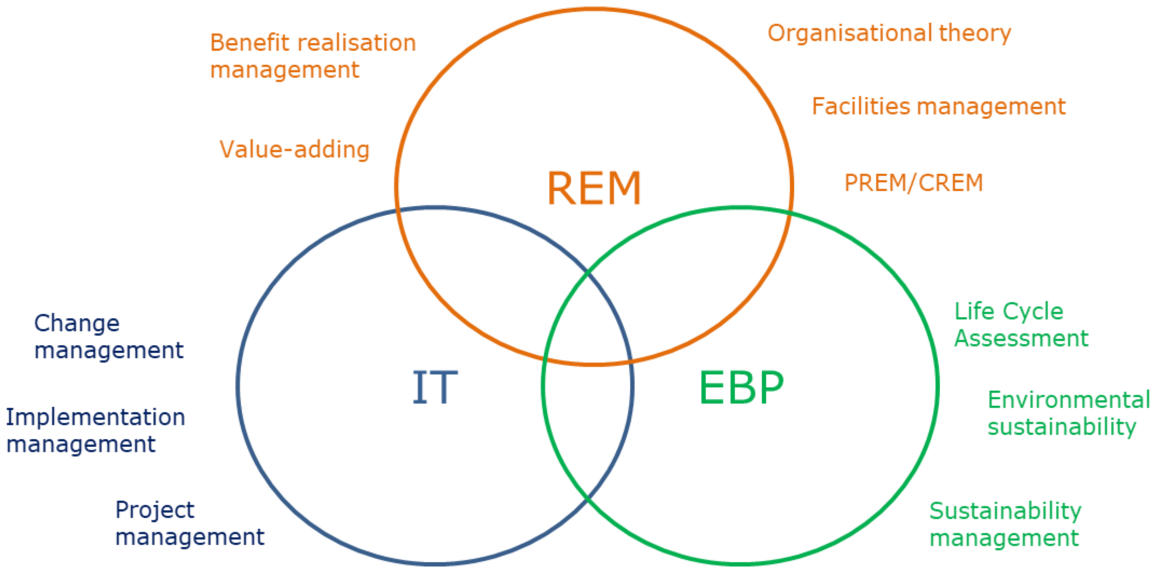

Figure 7: Theoretical framing within this PhD.

The following sections provide more detailed descriptions of each research field and highlight the important topics related to this PhD research.

3.1. Real Estate Management and Facilities Management

3.1.1. Definitions

Real Estate Management (REM) is very dependent on the context in which it takes place. In a commercial setting with a focus on real estate investments in property for renting out and/or selling, the aim is to get the best possible return on investment in both the short and long run (Van der Voordt, 2017). The situation is different in Corporate Real Estate Management (CREM), when the real estate is used by an organisation. CREM focuses on aligning real estate to corporate needs and objectives, incorporating the needs and wishes of shareholders and different stakeholders on the strategic, tactical and operational levels (Van der Voordt, 2017). Dewulf et al. (2000) define CREM as “the management of a corporations’ real estate portfolio by aligning the portfolio and services to the needs of the core business (processes), in order to obtain maximum added value for the business and to contribute optimally to the overall performance of the corporation”.

As both an academic discipline and a profession in practice CREM is closely related to Facilities Management (FM). FM is defined as an “organizational function that integrates people, place and process within the built environment with the purpose of improving people’s quality of life and the productivity of the core business” (Dansk Standard, 2018). Van der Voordt (2017) has made a comparison of CREM and FM, according to which CREM has its foundation in asset management, FM and cost control and is aligned to general management, while FM is characterised by its focus on non-core business services, workplaces and their management. Another difference is that CREM treats real estate as physical and economical assets utilized by an organisation, while FM has a wider focus on service, including demands related to space and infrastructure and to people and organisations.

In this dissertation, REM is defined as management of public real estate by a state agency that owns and lets out real estate to other governmental organisations such as ministries, agencies, the police etc. Concerning public real estate, the term Public Real Estate Management (PREM) is sometimes used as an analogue to CREM in private corporations. Moreover, in this research FM is defined as functions related to people, places and processes within the buildings that are used to support core business. The main case-study organisation, BYGST, is defined as a PREM organisation, while the three other cases are considered to be FM organisations. The major difference is that a PREM organisation's core business is the management of public real estate, while the FM organisations covered by this research are in fact business departments mainly responsible for building operations and maintenance (O&M) activities and workplace management with the aim of supporting the organisation's core business. The overall relationship between REM and FM in this PhD is shown in Figure 8.

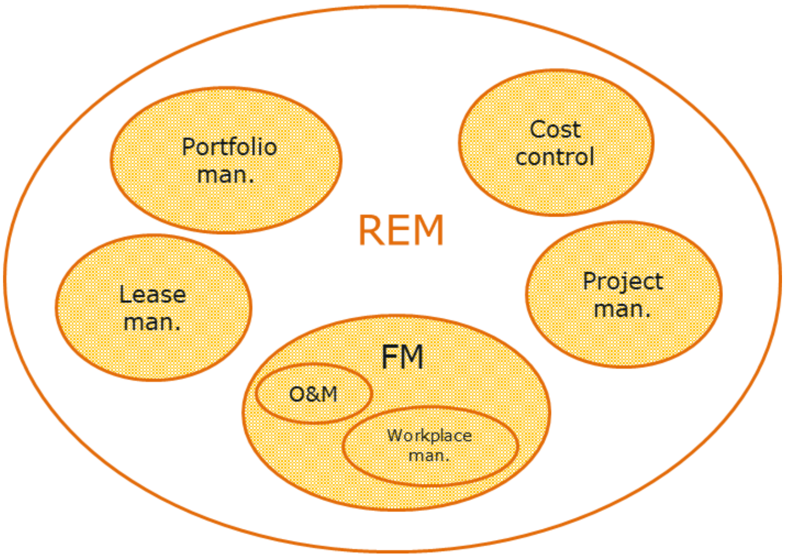

Figure 8: The relationship between FM and REM in the PhD.
FM is considered as an integrated part of REM.

In 2017, BYGST was given the responsibility for procuring and providing FM services to its customers, meaning that in the future BYGST will become responsible for both public real estate management and facilities management. This trend of combining public real estate management and facilities management has been covered previously in research (Van der Schaaf, 2002). One of the key findings was an ongoing shift from decentralised real estate management with a focus on facilitating primary processes to the integration of FM and CREM in centralised shared services. A recent book concerning facilities management and corporate real estate management as value drivers (Jensen and Van der Voordt, 2017) also indicates a trend towards greater integration of and convergence between corporate real estate management and facilities management.

3.1.2. Organisations and value-adding

When studying organisations, it is important to know how they are configured and what their value drivers are. These insights enable a better understanding of how certain technological changes impact on their configuration and core business. Each organisation consists of five basic parts: strategic apex, middle line, operating core, technostructure and support staff, as shown in Figure 9 (Mintzberg, 1980).

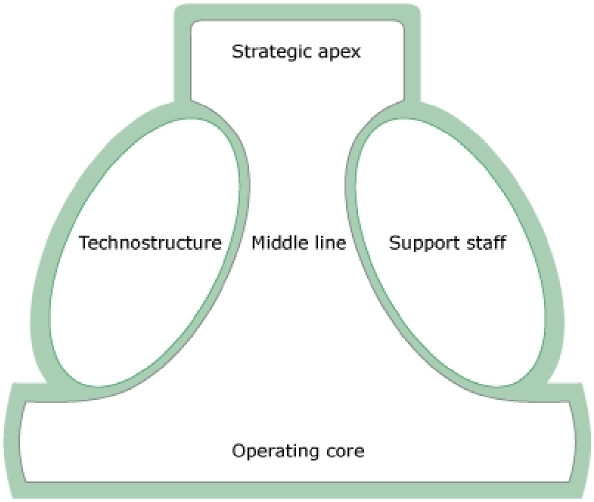

Figure 9: Five basic parts of an organisation (Mintzberg, 1980).

The organisational configuration can be impacted through the concepts of value-adding and benefit realisation. Jensen and Van der Voordt (2017) studied value-adding in FM and CREM and proposed a generalised Value Adding Management (VAM) model:

Intervention → Management → Added Value

Intervention is the general term for cause, Added Value the term for effect. To exemplify, implementing new IT systems in REM/FM organisations can be considered as an intervention directly impacting on their technostructure and affecting all three management levels, strategic, tactical and operational. The result might be improved effectiveness, increased efficiency or improved interoperability (Ebbesen, 2016). In this way, new IT systems might add value to the organisation, assuming that their implementation is managed properly and professionally. If there is a lack of management focus, it is likely that the IT implementation will fail.

To reduce the risk of failure, an agile approach to IT implementation is needed. Agility is the ability to manage and apply knowledge effectively, balancing change proficiency with knowledge management. Change proficiency determines the ability to deploy knowledge effectively. Knowledge management is about learning (what should be learned, when and how it should be learned, and who should be learning it) (Dove, 1999). Agile project management is therefore based on delivering requirements iteratively and incrementally throughout the project's life-cycle (Association for Project Management, 2018). An agile approach focuses on product quality and continuous improvement through lean thinking and customer input.

With agile project management, the relationship between knowledge management and change management must be addressed to determine how new knowledge and changes can add value to the organisation.

"Knowledge has no value until it is applied. When new knowledge is applied, it introduces a change into the environment, which generates a value." (Dove, 1999)

As Dove (1999) points out, knowledge which cannot be applied has no value. On the other hand, introducing new knowledge creates changes and adds value to the organisation. The true value of changes is determined by the benefits they bring to the organisation. Benefits are an outcome of change that is perceived as positive by a stakeholder (Bradley, 2016). In other words, benefits are strategic improvements in business value, usually achieved through programme and project management (Serra and Kunc, 2015). The creation of business value therefore depends strongly on programmes and projects delivering the expected benefits.

In parallel with the Value Adding Management model, the Benefit Realisation Management (BRM) approach can be useful when implementing new IT systems. BRM is the process of organising and managing so that the potential benefits arising from investment in change are achieved (Bradley, 2016). Implementing new IT systems brings about changes that can often lead to disquiet in the organisation, since there are many concerns for how the new IT system will impact on current workflows, internal collaboration, relationships with customers, managers etc. This is where benefit maps or "benefit realisation diagrams" can be beneficial, since they can create greater transparency and include customer inputs in their implementation. Benefit maps are networks of benefits that are usually linked to one or more of the primary investment objectives, and they map all the cause-and-effect relationships (Bradley, 2016). Benefit maps can show what the IT project must deliver and which internal changes the organisation must make in order to succeed.

3.2. Information technology in REM and FM (P3, P4)

The following section summarises theoretical frameworks from P3 and P4 relating to IT systems and implementation drivers, processes, data management, and the relationship between IT systems and EBP.

3.2.1. IT drivers

Technology is usually the element included to stabilise a rather fragile change in an organisation. Three dimensions are important when technology is used for change: coverage, functionality and dynamics (Kamp et al., 2005a). Coverage is the technological coverage of a company as the supplier imagines it. Functionality defines what the technology can do and is usually described in terms of modules or blocks. Dynamics highlight the fact that technology is not static but develops over time. Many dynamics are at stake after planned change. Internal and external development impacts on organisational change both intentionally and unintentionally. For example, intended internal changes within the organisation may be planned changes, while unintended external changes can include suppliers offering new system versions/updates or functionalities that, through their implementation, change parts of the organisation.

It is the influential factors from the business environment that determine the organisation's needs for IT systems. Gibler et al. (2010) found that organisations buy new IT systems for many reasons, but some of the most important include reducing transaction costs, reducing errors, enabling information-sharing, formalising business processes and increasing processing speed.

Historically the main driver for implementing IT in REM and FM was cost management. Managing facilities expenses is still an important consideration, but providing a more flexible workspace where people want to work has increased in importance. For example, a recent study conducted by Gartner showed that employees' working environments have a significant impact on their effectiveness and engagement, yet only 34% of workers like their workspace (Gartner, 2017b). Another aspect is that employees in the REM sector spend a lot of time in the field and need to be able to bring and complete their tasks remotely.

Business Process Reengineering (BPR) considers IT to be a tool for supporting and enabling changes in business processes. Reengineering restructures business processes across the entire organisation through radical thinking, while IT is only a lever for such processual changes (Hviid and Sant, 1994). IT systems must inevitably support activities relating to cross-disciplinary business processes and solve issues with long lead times and high management, administration and overhead costs, as well as break down barriers between subject areas and functions and between the organisation and its surroundings in general. The focus must be on customers' needs and value-creating processes (Kamp et al., 2005; Jensen, 2008).

The IT project is a process that begins as a concept and ends with actual implementation. It must therefore be managed as an organisational change project. The implementing conditions become more favourable when the benefits of the IT system are demonstrated during the implementing process (Madritsch and May, 2009), for example, through benefit maps. Benefit maps can be useful for highlighting the organisational benefits which the new IT system should deliver in order to be considered a successful implementation.

3.2.2. Implementation process

Implementing new IT systems can bring benefits to both REM and FM organisations. However, successful IT implementation is a complex process which normally concerns the entire organisation. IT implementation changes the technological component and thereby triggers changes in the other components of the organisation (Ebbesen and Bonke, 2014). The expansion of knowledge requires extensive input from the field. Communication and user involvement in the organisation in the early stage is crucial, especially because IT implementation typically runs over several years (Foley, 2012). IT implementations are cross-disciplinary and include different stakeholders (e.g. top management, consultants, system users). Determining the relationship between different stakeholders and new IT systems, as well as the impacts of the implementing process on the organisation, is therefore important.

Four dominant theories can be related to the implementation and adoption of IT: Technology Acceptance Model (TAM), Theory of Reasoned Actions (TRA), Diffusion of Innovations (DOI) and Theory of Planned Behaviour (TPB) (Korpelainen, 2011, p. 14). TAM is the most frequently cited theory, focusing on what causes stakeholders to adopt or reject the use of IT in respect of its usefulness and perceived ease of use. TRA defines the links between the beliefs, attitudes, norms, intentions and behaviours of individuals. DOI is a general theory of how new ideas are spread and adopted in a community, and it seeks to explain how communication and opinions shape adoption. TPB focuses on cognitive self-regulation. It is very similar to TRA, but the difference is that it also includes perceived behavioural control. Korpelainen (2011) also suggests the application of change management and change leadership, because IT adoption and implementation concern change and the acceptance of work tasks, processes and collaboration.

Implementing new IT systems in REM/FM organisations can involve improvements and changes to the technology (product innovation) and the business processes which the technology is meant to support (process innovation) (Ebbesen and Bonke, 2014). It can also cause or require improvements and changes in the organisation (organisational innovation), for example, through user trainings and education.

Identifying which changes will occur and ensuring the realisation of the desired benefits can be complicated. Success with IT projects depends on categories such as system quality, information quality, information use, user satisfaction, individual impact and organisational impact (Ebbesen and Bonke, 2014). IT systems that are not in line with company traditions and root processes have higher failure rates (Kamp et al., 2005a). Some IT systems are more complex than expected and bring unexpected routines to the organisation. Studying different critical factors can reveal whether implementation leads to failure or success. García-Sánchez and Pérez-Bernal (2007) found that most of the critical success factors in implementing IT systems were not technical, but included leadership, training, communication and cooperation. These findings are also supported by a CAFM market survey (GEFMA, 2017) showing that 35% of the implementation costs were direct software acquisition costs, while the remaining 65% were associated with hardware (3%), data capture (27%), data migration and customizing (24%) and user training (11%). The GEFMA study also showed that the costs of CAFM/IWMS implementation have changed over time, so that the costs related to user training and system customisation have increased (training costs from 25% in 2003 to 35% in 2017; customisation and data migration costs from 18% to 24%), while the hardware and data capture costs have decreased (hardware costs from 10% to 4%; data capture costs from 39% to 27% from 2003 to 2017).

These developments in cost distribution show that the implementation process and the users (the people) are at least as important as the software. Earlier research has concluded that the most successful IT implementation depends on a pace of change that the organisation and its people can support, meaning that business process and data governance need step change to evolve in line with the new technology (Hanley and Brake, 2016). The difference between successful and unsuccessful implementation seems to reside in planning, expectation-setting and managing the change within the organisation rather than in the quality of any one software vendor. Gibler et al. (2010) claim that some real estate departments implemented IWMS with excellent results and returns on investment, while other, similar organisations failed in the end due to problems related to poor planning, a lack of executive business sponsorship and mandate, oversold software and ineffective implementation teams.

3.2.3. IT systems and dynamic data

All real estates include physical systems like heating, lighting, plumbing and ventilation. The same real estates also include human systems (how occupants use the space) and assets and equipment that people need to perform their jobs. All these systems interact with each other and must be integrated. Therefore, there is a need for data on how each system works in relation to others (Short, 2017). Having access to facts and figures is not enough. To ensure knowledge and new insights, data must be interpreted in an appropriate way for different stakeholders. This is where IT systems show their value, as they must provide deeper insights into the data presented on the users' computer screens. The data analyses must be easy to understand, visually stimulating, accurate and convincing (Sandquist, 2015).

In this dissertation, the term "dynamic data" is used to define data that change over time. These data can be related to buildings (core data) or to their performance (e.g. consumption data). In general, performance data have higher updating frequencies than building core data since the latter are linked to the building's characteristics, like building area, age and location, while performance data depend on usage patterns that have higher variation over time. The IT systems studied in this PhD are considered to be mechanisms for data management and data analysis, as well as tools for supporting business processes related to REM and FM.

The four major IT system types within the Danish REM/FM sector have already been described in the Introduction. The research focus in this PhD was particularly on IWMS and EMS, as outlined in Section 2.2. In the following, more comprehensive definitions of the relevant IT systems are provided.

Integrated Workplace Management System (IWMS) is an advanced technological platform that combines relational data records for the building's stakeholders (employees, managers, tenants, suppliers etc.), assets (built assets, furniture, equipment) and business processes (workflows) to deliver deeper insights into real estate management across the entire organisation. The strength of IWMS is that its modules rely on a common database, which contains essential information on the building's stakeholders and assets, so the entire organisation uses the same database in a diversity of business processes.

Energy Management System (EMS) is a system used to monitor and manage electricity, heating and water consumption within buildings. The system automatically collects high-resolution consumption data by reading meters. The consumption data are typically reported to EMS every hour or half hour. EMS can be used as a stand-alone solution or be combined with other IT systems through an interface. Based on the consumption data, EMS can estimate GHG emissions for each consumption type and calculate different key performance indicators (KPIs) related to energy consumption in buildings. One of the most frequently used KPIs in EMS is consumption per area, for example, kWh/m^2.

Building Management System (BMS) is a system used for digitally monitoring the control and management of heating, ventilation, air conditioning (HVAC) and electrical systems in buildings. Compared to EMS, BMS is a more "technical" system, as it focuses on technical installations and their performance, while EMS concentrates on "raw" consumption data delivered from the meter readings. BMS and EMS are both considered point-systems, as they relate to one specific business area within REM, in this case energy management.

The common feature of described systems is that they all can be used for addressing environmental building performance. However, their core functionalities and workflows are different as they focus on different aspects of EBP. In the following, a more comprehensive picture of environmental sustainability in buildings is given, speficying which environmental categories should be monitored and benchmarked in practice through IT systems.

3.3. Environmental sustainability in buildings (P1, P2)

This section is based on a systematic literature review of EBP and sustainability in buildings. It summarises the main findings from P1 and P2.

3.3.1. Environmental building performance

Sustainable buildings, green buildings, low-energy buildings and smart buildings – nowadays there are many concepts addressing building performance and attempting to promote sustainability in buildings. The overall goal is to have high-performance buildings that accommodate different aspects of sustainability through their life-cycle (Lewis et al., 2010). Some aspects relate to environmental performance, but there are also economic (e.g. operational costs, rental costs, asset value) and social (e.g. safety, security, accessibility) dimensions that need to be considered (Haapio and Viitaniemi, 2008; Gou and Xie, 2018). However, the buildings and building construction sector combined are still responsible for 36% of global final energy consumption and nearly 40% of total CO_2 emissions (IEA, 2017). Moreover, the construction and use of buildings in the EU account for about 33% of water consumption, 33% of waste generation (European

Commission, 2017) and over 30–50% of total material use, depending on the type of material (Herczeg et al., 2014). In recent years, global use of energy in buildings has grown by 1% per year, and global building-related CO_2 emissions continue to rise by nearly 1% per year (IEA, 2017).

Related to the above facts, building performance assessments are extremely important, as they focus on the behaviour of a building under actual conditions of operation. Building performance assessments are seen as a mean to ensure that a building and its parts meet specific building requirements, as well as evaluating the built quality according to specific assessment criteria (Conte and Monno, 2012). Environmental Building Performance (EBP) focuses particularly on the environmental impacts of buildings during their life-cycle. Environmental impacts of buildings are typically summarized in two impact groups: embodied impacts (i.e. impacts embodied in the constructed building) and operational impacts (i.e. impacts while the building is being used) (Anderson et al., 2015; Soust-Verdaguer et al., 2016). The EBP depends on attributes such as building design, selection of building materials, quality of the construction work, building location, choice of energy supply source and operation and maintenance (O&M) activities (Harris, 1999; Pajchrowski et al., 2014). Once designed and built, it is not easy to change environmentally impactful decisions made in relation to the building design such as building orientation, window-to-wall ratios and HVAC systems (Russell-Smith et al., 2015). More importantly, the processes used for O&M activities have even larger cost and environmental impacts than the design and construction process (Khasreen et al., 2009; Lewis et al., 2010). Accordingly, this PhD focuses on use stage of buildings and its operational impacts.

Appropriate building life-cycle predictions are an important parameter for environmental building performance. Cabeza et al. (2014) noted that in research the reference life-time ranged between ten and a hundred years, with most of the research considering fifty years an appropriate reference life-time for a building's life-cycle. Grant and Ries (2012) argue that the reference life-time contributes significantly to expected environmental impacts by as much as 4–25%, depending on the impact category. These claims are also supported by a comparative study in which the maintenance impacts comprised 4–15% of the total impact (Junnila et al., 2006). Another comparative study of nine building-envelope systems concluded that maintenance-related impacts may range from between 2% and 55% of the total life-cycle impact, depending on the estimated service life, the estimated maintenance regime, and the frequency and intensity of replacement (Grant and Ries, 2012). The SLR in P1 found that most recent research used fifty years as an appropriate reference life-time.

3.3.2. Environmental performance of residential and commercial buildings

Several previous studies have examined environmental building performance. The environmental impacts are generally higher for non-residential buildings than for residential buildings. The average specific energy consumption in the non-residential sector is 280 kWh/m^2, which is at least 40% larger than in the residential sector (BPIE, 2011). While hospitals, hotels and restaurants represent the highest energy-intensive type in specific terms, offices, wholesale and retail trade buildings represent more than 50% of energy use. A comparative study of thirteen buildings found that commercial buildings had significant impacts on the environment compared to residential buildings (Sharma et al., 2011). By comparing variables like building location, building type, life-time (year), floor area and energy use, the study showed that aggregated greenhouse gas (GHG) emissions could amount to 5,600,000 t for commercial buildings and 5.4 t for residential buildings. The study also concluded that 80–85% of total energy consumption in a building's life-cycle occurred during the stage of occupancy. Another study among 73 case-study buildings from thirteen countries found that the Energy Efficiency Index values of office buildings were slightly higher than those for residential buildings (250–550 kWh/m^2/year for office buildings; 150–400 kWh/m^2/year for residential buildings) (Abu Bakar et al., 2015). Asdrubali et al. (2013) showed that the operational stage made the greatest contribution to the total impact (from 77% for a detached house to 85% for an office building), whereas the impact of the construction stage ranged from about 14% (office building) to 21% (detached house).

P1 found that the operating energy of buildings usually accounted for 80–90% of their total environmental impacts, while embodied energy accounted for the remaining 10–20%. From a life-cycle perspective the EBP also differed between older and newer buildings. While older buildings had the highest environmental impact during the use stage, newer buildings showed burden-shifting tendencies towards increased embodied impacts, because of lower operating impacts. Older office buildings especially caused large environmental impacts, since they generally required more energy during the use stage compared to residential buildings. Still, most recent research focuses on residential buildings, indicating a lack of research on environmental building performance in the non-residential sector.

Relating to the above findings, this PhD concentrates on the use stage of commercial (mainly office) buildings. The research covered in P1 emphasised that over 90% of the energy consumption of commercial structures across the life-cycle and 80% of the carbon dioxide emissions come in the use stage of the building (Russell-Smith et al., 2015). A study of an office building in Finland showed that most of the covered impacts were associated with electricity use and the manufacture of building materials (Cabeza et al., 2014). In particular, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing and the maintenance of steel, concrete and paint, as well as waste, were identified as the most impactful activities. Another study showed that the use of building materials, energy consumption and disposal of waste caused 12-35 times higher environmental impacts in the use stage than the production of building materials. The operating energy consumption was highlighted as the main source of negative environmental impact (Pajchrowski et al., 2014).

In general, operating energy consumption is heavily influenced by choices relating to building envelope, glazing, the thermal mass of the building's structure, insulating materials, day-lighting and lighting control, natural ventilation and energy-recovery opportunities, and HVAC systems and operational modes such as temperature and air volume control, motors and pump types of control, indoor and outdoor air quality, and environmental protection (Kim and Todorovic, 2013).

3.3.3. Quantifying EBP

Many assessment tools based on performance indicators have been developed for quantifying EBP. For example, Pons and Aguado (2012) have identified ten environmental impact assessment tools for buildings. Most of them are complex rating tools in which the assessment is made by certifying specific weights to different criteria (Russell-Smith et al., 2015). Environmental assessment tools have some common features, being environmentally driven, based on indicators of building performances, and score based (Conte and Monno, 2012).

P1 and P2 identified two approaches for quantifying environmental building performance. The first approach is based solely on life-cycle assessments (LCA), while the second approach encompasses criteria-based certification tools, which in some cases also rely on an LCA approach. Among the most widespread certification tools are BREEAM, LEED, CASBEE, SBTool and Green Globes, all multi-criteria systems aiming to cover the environmental, economic and social aspects of sustainability. In the selection of assessment criteria, the environmental aspects receive much more attention than the economic and social ones. Energy efficiency is considered the most important category of certification tools, followed by indoor environmental quality, waste and pollution. In Denmark, a DGNB certification, based on a tool originally developed in Germany, is used. The development of DGNB certification tool has placed an increased emphasis on the quality of the building and its functional aspects, with social integration being taken into account more than in the other certification tools (Berardi, 2012). Certification tools are closely linked to market interests and stakeholder culture (Berardi, 2012), but they can lead to erroneous conclusions seen from a scientific point of view (Elle *et al.*, 2010). On the other hand, Life Cycle Assessment (LCA) has previously proved to be an accepted scientific method for assessing environmental building performance (Anderson et al., 2015; Lotteau et al., 2015; Passer et al., 2016). Thus, this PhD adopted an LCA approach in quantifying the EBP of eighteen office buildings (P6). LCA is an internationally standardized method of accounting for all inputs, outputs and flows within a process, product or system boundary in order to quantify a complete set of environmental, social and economic performance indicators (Russell-Smith et al., 2015). The fundamental LCA framework and principles are outlined by ISO 14040, and the requirements and guidelines are given in ISO 14044. In addition, EN 15643 covers the sustainability assessment of buildings, while EN 15978 provides the basis for the environmental performance assessment of buildings (Anderson et al., 2015).

When quantifying the results with LCA, one main distinction is that between midpoint and endpoint impact assessment methods, which look at different stages of a cause-and-effect chain. An endpoint method looks at the environmental impact at the end of a cause-and-effect chain, while the midpoint method looks at the impact earlier along the chain, before the endpoint is reached (Brilhuis-Meijer, 2014).

Although LCA is mainly used during building design, this assessment method can also be applied in respect of building operations. In building renovation projects, LCA, for example, is suitable for the comparison of several products, building strategies or building components that fulfil renovation criteria (Ohms et al., 2018). LCA can also be used for evaluating environmental building performance across property portfolios. By means of a detailed result analysis, LCA can identify the weakest environmental points in buildings and highlight the most environmentally friendly solutions. However, there are several barriers to applying more dynamic LCA approaches in practical building operations, including the perception that the LCA method is already highly data-demanding and work-intensive, and consequently more costly. It has also been noted that using LCA building tools requires a high degree of knowledge. Other barriers to the use of LCA in general include prejudices about its complexity, the arbitrary nature of its results, its accuracy and problems in interpreting its results (Malmqvist et al., 2011). Furthermore, application of the LCA method does not guarantee a reduction of emissions or energy consumption, though it does identify environmentally weak points of products (e.g. buildings), as well as hotspots for improving their environmental performance (Proietti et al., 2013).

3.3.4. Environmental categories for building performance

In the facilities management sector, European Standard EN 15221-7 sets out guidelines for performance benchmarking and provides a range of key indicators to identify areas in which performance might need to be improved (Dansk Standard, 2012). Furthermore, Key Performance Indicators (KPIs) are popular in FM, as they are suitable for monitoring and controlling the desired outcomes of buildings. KPIs help FM organisations to focus on the potential benefits in relation to the resources spent (Jensen et al., 2012). Environmental KPIs are usually grouped into several categories. For example, Kylili et al. (2016) divided the environmental category into twelve sub-categories, while Toller et al. (2013) used six indicators for environmental monitoring of the Swedish building sector. Alwaer and Clements-Croome (2010) identified sixteen impact categories related to sustainable buildings, of which six concerned environmental indicators.

In P1, the systematic literature review of 69 research articles revealed the existence of eight important categories for EBP. Table 3 shows the identified categories with examples of their KPIs. The categories are ranked in prioritised order in accordance with the number of articles identified within each environmental category.

Rank	Environmental category	Examples of KPIs and their units of measurements
1	*Energy*	Energy consumption (kWh, MWh, GJ) Energy-saving potential (kWh, MWh, GJ or %) Energy supply (renewable/non-renewable %)
2	*Emissions*	GHG, e.g. CO_{2e}, NOx, SO_x
3	*Water*	Water consumption (m^3) Water-saving potential (m^3 or %) Water supply – local, rainwater (m^3 or %) Water pollution
4	*Waste*	Daily waste (kg, t) Building waste (kg, t) (production, treatment, disposal)
5	*Land/building area*	Property site (m^2) Total building area (m^2) Capacity (m^2/person), Occupancy rate (%)
6	*Building materials*	Aesthetics/building design Durability (years) Thermal properties (U-value) Maintenance properties
7	*Indoor Environmental Quality (IEQ)*	Thermal comfort (°C) Relative humidity (%) Daylight Air quality (ppm)
8	*Reuse/recycle potential*	Building components Building materials

Table 3: Environmental categories identified in systematic literature review.

P1 identified energy and emissions as the two most dominant environmental categories. Energy was addressed in 40 out of the 69 articles, while 36 focused on emissions. The energy category included KPIs relating to energy consumption, energy-saving potential and energy supply distribution (renewable/ non-renewable energy). The emissions category addressed climate change impacts through the KPIs on emissions of GHGs such as CO2e, NOx, SO_X etc. The water category ranked third and was dealt with in 21 of the 69 articles. This category usually included KPIs relating to water consumption, water-saving potential, water supply, water pollution etc. The waste category was considered in eighteen articles and typically used KPIs to show how much daily waste and building waste is produced, treated and disposed of. Land and building area use appeared in thirteen articles. The land and building area category focused on KPIs relating to space management inside and around buildings and on how efficiently building space was utilized. Building materials were studied in ten articles. This category concerned building materials used in constructing or renovating buildings. KPIs for building materials usually covered building material properties such as aesthetics, durability, thermal properties and maintenance properties. The least research focus was on indoor environmental quality (IEQ) and reuse potential, covered in just nine articles, while only four focused on reuse potential. The IEQ category included KPIs like thermal comfort, daylight and air quality. IEQ indicators were often described as social indicators, but since many IEQ indicators have an impact on EBP, in this research they are considered an environmental category. Previous studies, mostly focusing on office buildings, have shown that their occupants' health and well-being can be affected by various indoor environmental parameters, such as temperature, humidity, ventilation, natural lighting or illumination and noise (Huang et al., 2013). The reuse and recycling potential category considered the potential for recycling and/or reusing existing building components and materials for other purposes after their lifetime had ended. This category was only considered in four of the 69 articles and was usually related to studies in which the whole of the building's life-cycle is covered, including the end-of-life stage.

The following section shows which of the environmental categories from Table 3 are used in practice, and how they are managed through IT systems used by the organisations studied.

4. CASE STUDIES

This section presents the four selected organisations, showing how they use their IT systems to manage EBP. More details can be found in P3, P4 and P5.

4.1. Case I: Bygningsstyrelsen

4.1.1. About Bygningsstyrelsen

Bygningsstyrelsen (BYGST) is the Danish state's property enterprise and developer, its main task being to provide work spaces and office and research environments on market terms for its customers, including universities, the central administration, police and the courts. BYGST was established in October 2011 as part of a Danish government reorganisation in which several governmental agencies consolidated into it. The agency carries out its task by owning and renting out the state's buildings through buying existing buildings, new construction and modernisation, and by redistributing private leases to state institutions. In January 2019 the agency moved into its new headquarters in Copenhagen (Figure 10). BYGST has over three hundred employees, who manage 1,800 leases covering more than 4 million m^2 of building area. About 1.2 million m^2 are private leases and public–private partnerships, 2 million m^2 are used by the universities, and approximately 800,000 m^2 are office buildings owned by BYGST (Bygningsstyrelsen, 2017c).

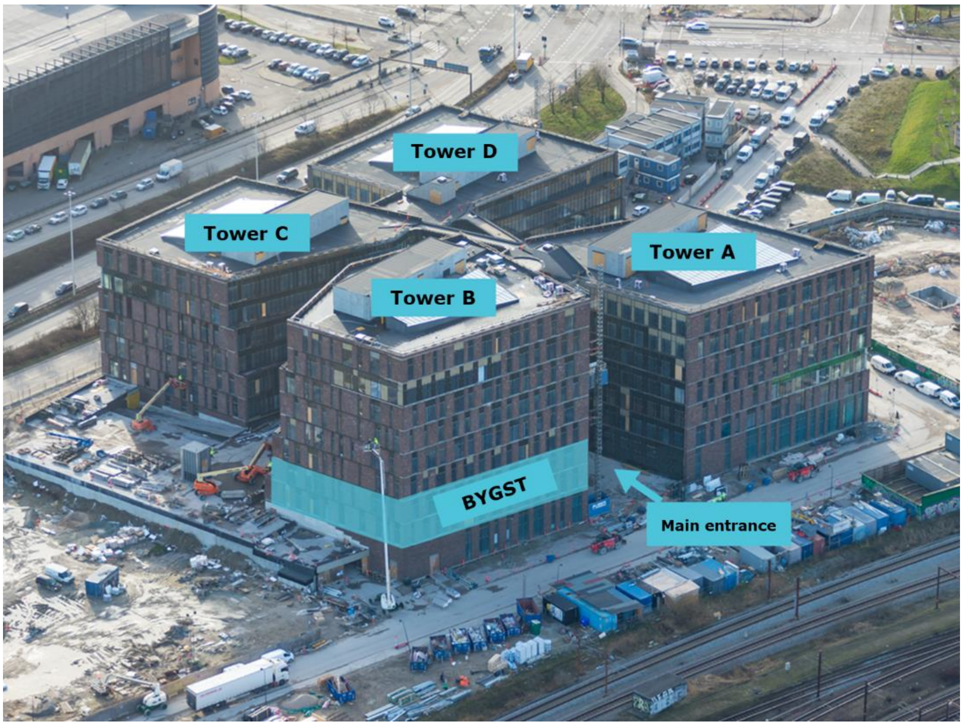

Figure 10: Bygningsstyrelsen's new headquarters in Copenhagen. BYGST is situated on 1st and 2nd floor in Tower B. The remaining area is used by other ministries and agencies. The property is developed as public-private partnership (Photo: bygst.dk).

Because of former reorganisations, different employee needs and working cultures, BYGST, as a relatively new PREM organisation, faced many challenges from its accompanying IT system landscape. The agency had a broad pallet of silo-based systems, which supported the specific needs of different departments but caused many challenges in maintaining and developing some of these IT systems. Moreover, several IT systems contained same types of data, which were updated individually in each system, leading to a lack of coordination and poor data quality. BYGST therefore needed a more consolidated IT system landscape that could reduce the number of IT systems and ensure consistent, valid data across the entire organisation.

To solve the problem, in 2013 BYGST initiated a comprehensive market survey to change the IT system landscape. The agency had several requirements for the future system:

- The system had to be a standard system already in use in similar organisations to BYGST
- It had to have a core database in which all information and data could be stored in versions with logs and security
- It had to support the functions of 80% of BYGST's single-point systems and databases (approximately 25 systems)
- It had to be easy to upgrade to new versions without involving software developers, but using business specialists

4.1.2. Implementation process

Initially, more than fifteen software providers (six IWMS providers and eight to ten larger CAFM providers) were invited to present their products and solutions. Both Danish and international products were reviewed, a process indicating that IWMS was the most suitable system type for BYGST, having been developed and used by other similar REM organisations. Consequently, the agency studied Gartner's "Magic Quadrant" (vision/execute maturity matrix, shown in Figure 11) to identify potential IWMS providers.

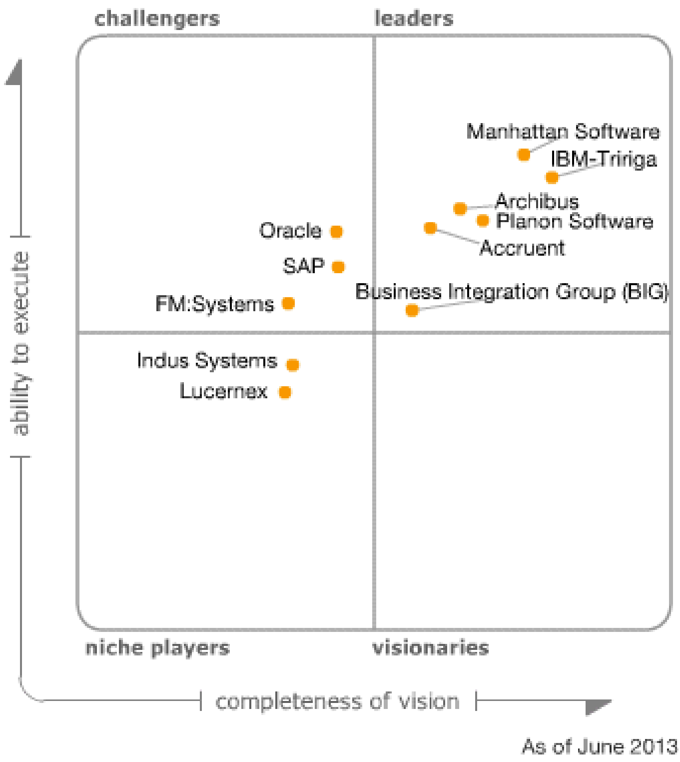

Figure 11: Magic Quadrant for Integrated Workplace Management (Gartner, 2013).

The quadrant identified four international software providers (Manhattan Software, IBM Tririga, SAP and Planon Software) as capable of fulfilling BYGST's needs and demands. In spring 2014, BYGST invited the four providers to a technical dialogue, which revealed that only one or two IWMS providers could match BYGST's actual requirements on cross-module functionality, consultancy, safety, and visions for future demands and functions (Bygningsstyrelsen, 2017b). Subsequently, BYGST visited several foreign REM organisations (the Dutch Building and Property Agency and four companies and municipalities in the UK) which were already using IWMS to gain more knowledge of the system and how it could be used in practice. Furthermore, BYGST had several knowledge-sharing sessions with Danish companies that were using IWMS, like Novo Nordisk and Lundbeck, to gather information about their experiences, recommendations, implementation times and financial costs etc. The market survey took two years (2013-2015). Based on the inputs from other REM organisations and the market survey, BYGST decided to introduce IWMS for their organisation (Bygningsstyrelsen, 2017b). This made BYGST the first PREM organisation in Denmark to introduce IWMS, making them the pioneer in the field.

The tendering process took place in spring 2015, being based on rules regarding public procurement. Based on the tendering criteria, BYGST selected "KMD Atrium" (Manhattan Software) as the most suitable IWMS solution. Since "KMD Atrium" was a completely new product in Denmark (as well as in KMD's product portfolio), and because BYGST was the first Danish PREM organisation to implement IWMS, the parties initially agreed to test the system through a Proof-of-Concept (PoC) exercise in which system functionalities and features could be demonstrated to future users at BYGST. The PoC took place between autumn 2015 and autumn 2016 and included system demonstrations of each IWMS module. In October 2016, after a successful PoC, BYGST approved full implementation of "KMD Atrium". Initially the agency decided to implement five IWMS modules, as shown in Figure 12: Core, CRM (Customer Relationship Management), Lease, Project and Energy.

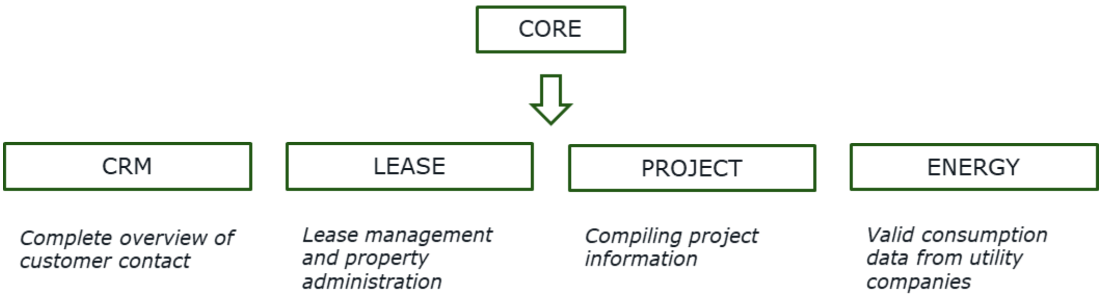

Figure 12: "KMD Atrium" modules implemented at BYGST and their functions.

Each IWMS module covers a specific business area related to REM:

- The Core module manages data relating to properties, buildings and their users. The module is based on the Object-oriented Input System (OIS) database, which provides data on building owners and tenants, property/building numbers, addresses, area size of various types, cadastral area, year of construction etc.
- The CRM module is used for processing and documenting all requests, questions, complaints etc. from the current and future tenants of the buildings in the BYGST's portfolio.
- The Lease module manages processes relating to tenants and lease administration. The tenant's cycle covers the processes of moving in and out and the period of the actual lease agreement.

- The Project module allows BYGST to record new construction projects, their milestones and documentation. Projects are used to record when a request has moved out of the CRM cycle and has been passed to the project management team.
- The Energy module is used for strategic reporting on EBP. The module collects, analyses and benchmarks dynamic data on electricity, heating and water consumption from EMS. The module also calculates and reports GHG emissions.

IWMS implementation was based on the agile project approach. This approach enabled IT implementation to be divided into smaller work packages which could each deliver specific benefits related to the specific IWMS module and could be completed within short timeframe (less than a year). Implementation included high-level (HLD) and low-level system design (LLD). In HLD, the system's requirements were specified. In LLD, the implementation project was divided into several sub-projects. This meant that the entire IWMS solution was not configured, tested and implemented at once, but implemented in the form of short, manageable, robust sub-projects. There were five sub-projects, one for each IWMS module. Each sub-project included four stages (design – build – test – deploy) and potential integrations as shown in Figure 13. The five sub-projects were initiated in August 2017 and ran until May 2019.

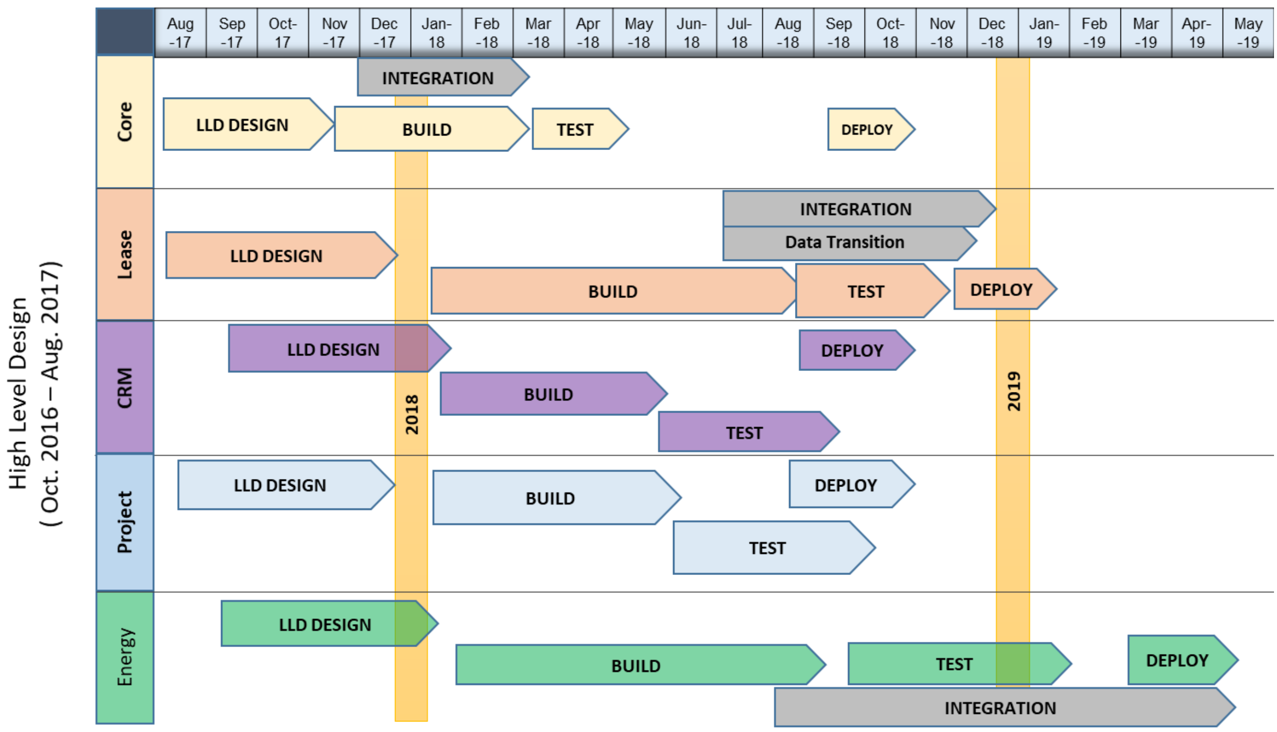

Figure 13: Timeline for IWMS implementation at BYGST (Source: KMD/Trimble).

Besides the five IWMS modules, four integrations with other IT systems and databases formed part of the implementation project. The integrations covered two-way integrations with EMS "KMD EnergyKey" and financial system "Navision Stat", a one-way integration with the central building database "KMD Cognito" ("KMD Cognito" is the master), and an IWMS integration with Trimble Connect, a project collaboration platform for the construction industry.

In the beginning of the IT project, a high-level design document (HLD) was created by KMD and Trimble briefly summarising the project's scope, the main functions of each module, integrations, crossovers, data requirements, security etc. The HLD document needed to be approved by BYGST for further implementation. Once it had been approved, the LLD was initiated. In the design stage, low-level design (LLD) documents were created for each IWMS module providing more comprehensive descriptions of each module. The LLD documents were used for system configuration and as system documentation for the customer. The LLD documents contained in-depth information on data sources, module structure, system design (screens/dashboards), integrations and user set-up. Each LLD document had several revisions based on the ongoing inputs and demands from BYGST. After LLD documents had been approved by BYGST's representatives for each module, the build stage was initiated. The build stage included several sprints (development phases) and implementation workshops for each IWMS module. The workshops presented progress already made, together with the challenges and the possibilities of further system configuration. In the test stage, the modules were tested and adjusted to customer needs, depending on the scope of the LLD documents. In the deployment stage, the modules were launched, with KMD offering system support on site.

Four organisations were involved in the implementation: BYGST as the customer, KMD as the IWMS and EMS provider, Trimble as the software developer and Implement Consulting Group (ICG) as an external consulting company hired by BYGST to be responsible for change management. The official implementation team included 35 people: fourteen from BYGST, twelve from Implement Consulting Group, five from KMD and four from Trimble. Besides the official implementation team, many other employees from all four organisations were involved in the implementation as required.

ICG and BYGST created a benefit realisation map for each sub-project (IWMS module) showing which software deliveries had to be provided, but also indicating which internal organisational changes were necessary for successful deployment of the module. The benefit maps highlighted, which benefits each module was expected to bring to a relevant department, as well as to BYGST as an organisation. An example of a benefit map for energy management developed by ICG and BYGST can be found in P3.

During the PhD, the researcher was at one point involved in the actual implementation of IWMS and EMS. The researcher acted as KMD's assiting business specialist for IWMS Energy module for a few months and was threfore involved in meetings regarding system design for energy management at BYGST. The researcher was also involved in collecting consumption data from different sources (utility companies) in EMS. Thus, the researcher particularly followed and studied the Energy sub-project, as this was related to EBP and to the research fields covered by this PhD. In the following, a more detailed description of the Energy sub-project is provided, based on action research and data collected though the document studies, field observations and interviews.

4.1.3. Managing EBP through IT systems at BYGST

Before IWMS and EMS implementation, EBP was managed by means of several IT systems and data loggers. The energy-specific systems and data loggers were replaced by the new energy management model presented in Figure 14. The EBP relates mainly to energy management (electricity, heating and water consumption) and emissions reporting.

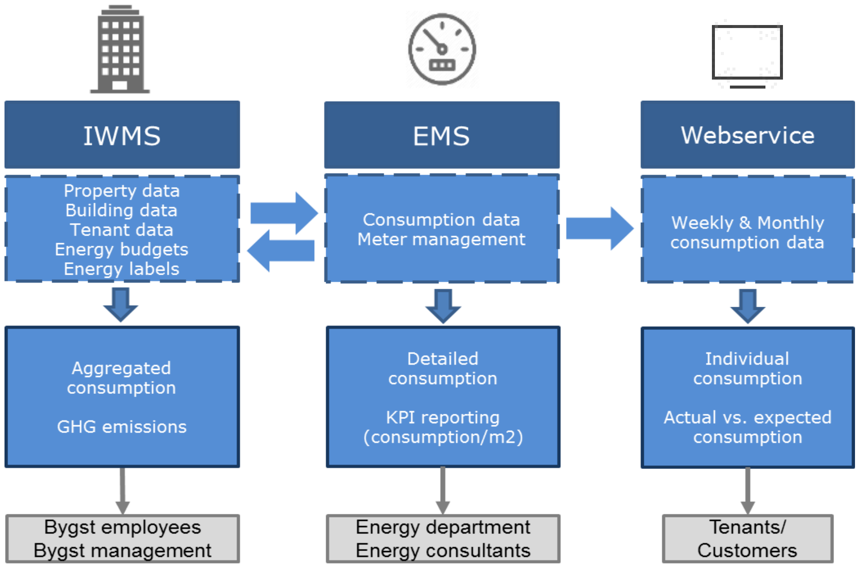

Figure 14: New energy management model at BYGST (P3).

Besides the IWMS Energy module, the EMS and the connected webservice solution were also included in the energy management. The EMS focuses on energy data collection, meter readings, data analysis, consumption visualisation and reporting. The webservice is an add-on module to EMS that displays individual energy consumption to end-users, in this case BYGST's tenants. Since IWMS is the master in building data and EMS in respect of consumption data, a two-way Application Programming Interface (API) is being developed for data exchange. The API is expected to be fully developed by spring 2019.

The consumption readings were collected earlier in different formats by using data loggers and both automatic and manual meter readings. This reading process caused data inconsistency due to different reading formats, different frequencies and technical failures (interview, technical consultant). Currently, 95% of electricity, 65% of heating and 35% of water consumption data in office buildings are delivered directly from the utility companies to EMS through remote readings (Bygningsstyrelsen, 2017a). The remaining consumption is still collected through data loggers, but over time it will be delivered directly by the utility companies. The Danish Meteorological Institute delivers degree-day data to EMS daily, and heating consumption is benchmarked right away, regardless of weather conditions.

EMS is used by the Energy department and operates as an engine for meter management and consumption readings. It provides deep insights into the energy performance of each BYGST lease unit, building and property. Energy management reports electricity (kWh), heating (kWh) and water (m^3) consumption on different building levels (property-building-lease unit) and for different tenants.

Figure 15 shows parts of the EMS solution for managing heating consumption at BYGST. The figure shows heating consumption in an office building between May 2017 and December 2017. Besides actual consumption ("consumption"), the system shows expected consumption ("budget"), degree-day adjusted consumption ("adjusted consumption"), energy savings and cooling efficiency. Furthermore, the system automatically calculates and presents KPIs such as kWh/m^2 and m^3/m^2 (hot water usage (m^3) per m^2).

Period	Budget	Adjusted Budget	Consumption	Savings	Savings [%]	Ref.	Cooling
May 2017	23,350.80	21,796.03	23,399.91	-1,603.88	-7.4	530.31 m³	37.9 °C
Jun 2017	11,949.15	8,262.12	7,600.09	662.03	8.0	194.39 m³	33.6 °C
Jul 2017	6,026.21	5,685.64	5,820.32	-134.68	-2.4	159.61 m³	31.4 °C
Aug 2017	6,618.50	4,308.56	5,469.72	-1,161.16	-27.0	151.09 m³	31.1 °C
Sep 2017	17,279.79	15,384.45	19,350.10	-3,965.65	-25.8	491.20 m³	33.9 °C
Oct 2017	33,567.87	28,918.36	37,029.79	-8,111.43	-28.0	964.70 m³	33.0 °C
Nov 2017	54,298.15	50,996.11	63,640.13	-12,644.02	-24.8	2,017.69 m³	27.1 °C
Dec 2017	68,809.34	61,612.97	74,740.24	-13,127.27	-21.3	1,709.00 m³	37.6 °C
Total	**484,847.08**	**435,864.39**	**502,920.41**	**-67,056.02**	**-15.4**	**12,407.09 m³**	**34.9 °C**
Prognosis	**484,847.08**	**435,864.39**	**502,920.41**		**-15.4**	**12,407.09 m³**	
kWh/m²	**88.46**	**79.52**	**91.76**			**2.26 m³/m²**	

Figure 15: EMS solution for BYGST (Source: KMD EnergyKey).

Tenants have access to the webservice solution called "Webtools", where they can log in and follow their electricity, heating and water consumption. Figure 16 shows the webservice solution for Lease A. When logged in, the tenant can see and benchmark actual consumption with expected (i.e. last year) consumption.

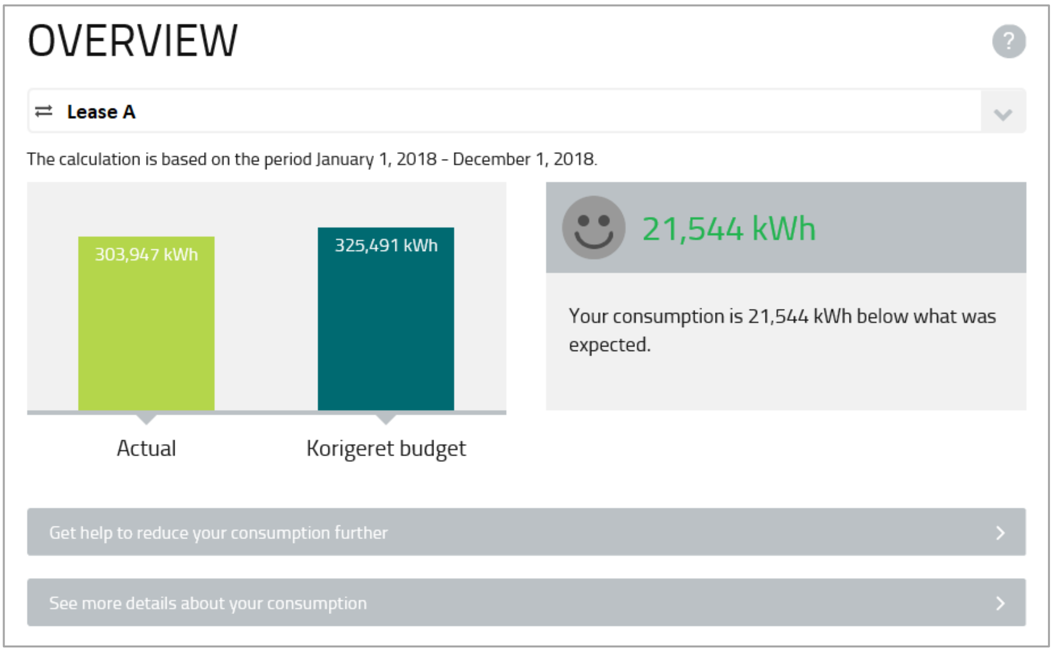

Figure 16: Webservice solution for BYGST's tenants (Source: Webtools).

Besides monitoring and benchmarking overall consumption, Webtools are also configured to display hourly consumption. Figure 17 shows how Webtools display hourly consumption for end-users (BYGST's tenants).

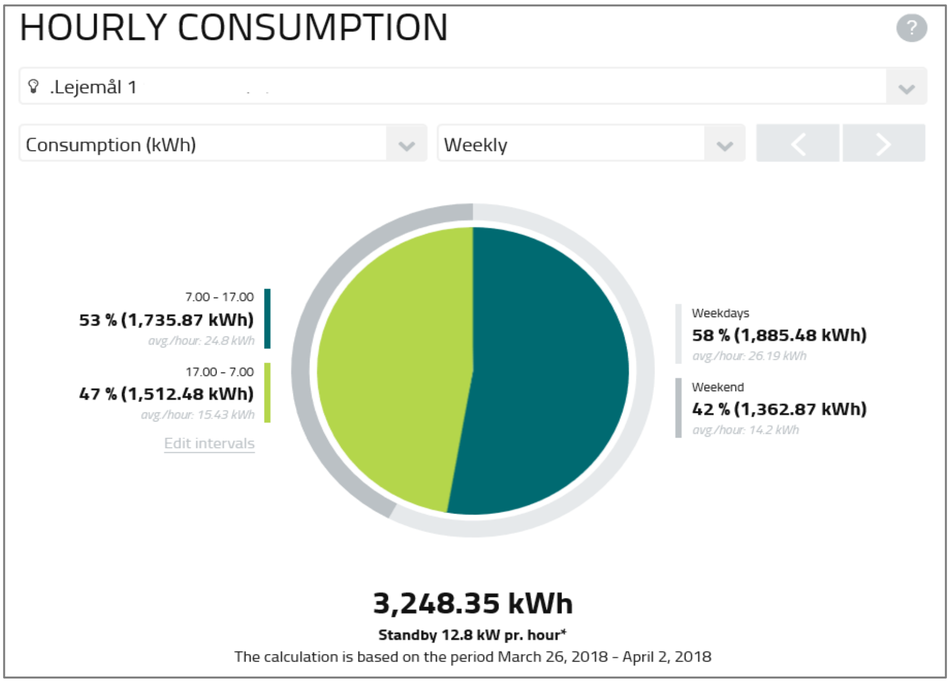

Figure 17: Electricity consumption distribution in Lease 1. The data are for week 13 (26.3. – 2.4.2018.) (Source: Webtools).

The webservice is configured to display consumption for working hours (7.00-17.00), non-working hours (17.00-07.00) and weekends. The facilities managers also have access to the webservice and can see how much energy is used during working hours, outside working hours and at weekends. This feature can be useful for identifying potential energy waste outside working hours. Moreover, the data are also useful for benchmarking energy consumption between tenants and for monitoring stand-by consumption.

The benefits of new energy model are documented and followed through benefit realisation map presented in P3 (p. 6), hightlighting the realised goals. The benefits of implementing new energy management model at BYGST included improved data quality, faster (automated) data harvesting from the utility companies, increased employee satisfaction with the IT solution due to automatisation, and better customer service, as the customers now have online access to their own energy consumption. Regarding environmental building performance, the implemented solution provides more detailed, high-resoulution (hourly) consumption data on electricity, heating and water consumption. The new energy management model enables the consumption data to be presented in new formats (e.g. Figure 17), highlighting the potentials for energy savings within and outside of working hours.

4.2. Case II: KMD

4.2.1. About KMD

KMD is the largest IT company in Denmark and has more than 3,200 employees. It provides IT services primarily to public bodies, but also has business in the private IT sector, both domestically and in Sweden and Norway. KMD has a total building portfolio area of approximately 105,000 m^2 divided across the four largest cities in Denmark. Figure 18 shows KMD's headquarters in Ballerup (Greater Copenhagen). The company has also departments in Aarhus, Aalborg and Odense.

Figure 18: KMD's headquarters in Ballerup (Photo: kmd.dk).

All Danish locations are ISO 14001 certified. ISO 14001 is the international standard for environmental management. The company sorts biowaste in canteens and uses follow-me print to reduce printing waste. The waste containers have sensors so that they are only emptied when they are full. Furthermore, the company issues annual CSR reports.

In April 2016, KMD carried out a large reorganisation of the FM department and reduced the number of employees from 28 to 16. The new FM organisation is now divided into hard and soft service departments. The hard FM department is responsible for the operation and maintenance of office and production (IT-server) buildings and handyman tasks. The soft FM department is responsible for cleaning, reception, canteen, travel arrangements and administration. The number of FM service providers were also reduced from 78 with or without service agreements to sixteen with service agreements. The new FM service providers are national and thus able to deliver service at all KMD locations. In relation to the FM reorganisation, it has been decided to implement parts of IWMS "KMD Atrium" (FM portal) and EMS "KMD EnergyKey" to support the change process and strengthen the new hard FM department.

4.2.2. Managing EBP through IT systems at KMD

Before IWMS and EMS implementation, the FM department used Microsoft Excel as the FM system for many years. The employees stored different types of FM data, including energy data, in the Excel spreadsheets and developed different KPIs for performance benchmarking. Many of the data-collecting processes were manual, meaning that FM personnel had to collect and register the data in the system themselves. Furthermore, it was difficult to categorise some FM data, since it could be reported to the FM department in different ways (telephonically or via email), meaning that there was no standardised method of collecting the data.

As regards environmental sustainability, the company has been using Excel almost ten years for monthly reporting and benchmarking of energy consumption across locations and usage types. As an IT company with a lot of IT equipment the electricity data had the highest priority, and consumption was benchmarked between offices, print centres and data centres. Figure 19 shows how Excel was used for the monthly reporting and monitoring of electricity consumption across three usage categories (offices, print centres and data centres) and total electricity consumption.

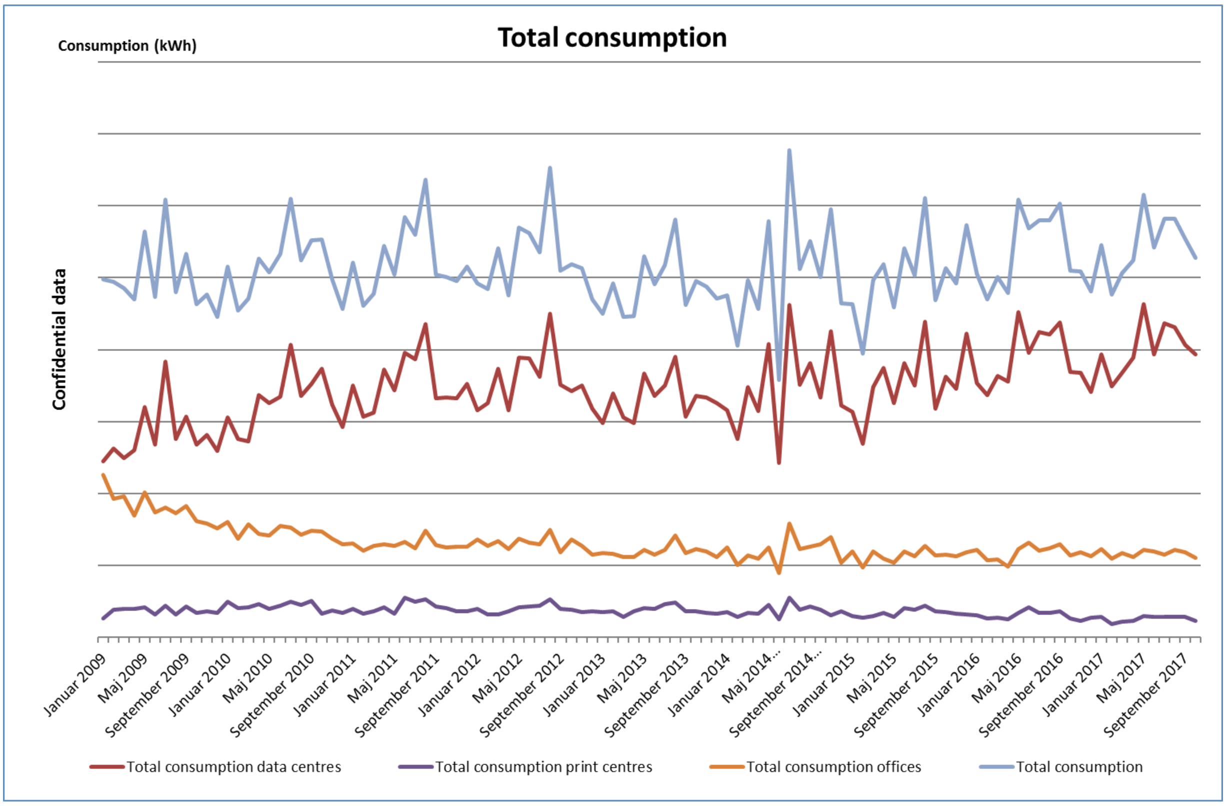

Figure 19: Visualisation of KMD's electricity consumption (January 2009 – September 2017). Monthly consumption. The consumption is divided between data centres, print centres, and offices. The actual consumption is confidential (Source: KMD FM department, Excel).

Electricity consumption across office locations was also benchmarked in Excel, as shown in Figure 20. The figure shows that some locations have reduced their electricity consumption, others have slightly increased it, while most locations have had almost constant electricity consumption over time.

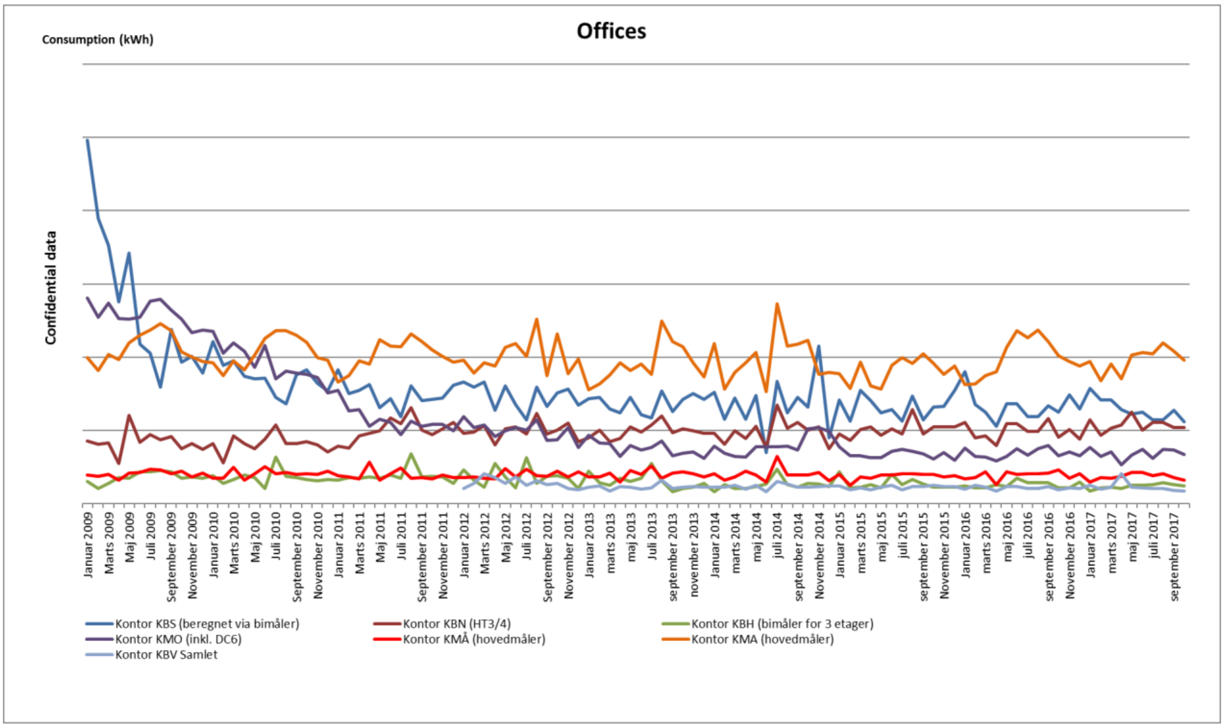

Figure 20: Electricity consumption across building locations (January 2009 – September 2017). Monthly data readings. The actual consumption is confidential (Source: KMD FM department, Excel).

Besides electricity, heating and water consumption was also monitored and benchmarked in Excel. However, large resources were required to collect the consumption data from different locations across the country. According to the FM director, at least one working week was spent each month on collecting, importing and processing consumption data in Excel. This data collection method enabled KMD to have a monthly overview of its energy consumption between different usage categories, but it also entailed certain limitations. For example, the data had monthly resolution, meaning that it was not possible to zoom in and see more detailed, daily or hourly energy consumption and acquire more exhaustive insights into energy performance. Moreover, the manual data collection also involved the risk of human error, when importing the data to Excel due to misreadings and typing errors.

Due to the reduction of human resources in the FM department after the reorganisation, the company needed to standardise and automate the business processes related to FM data collection in order to maintain its work efficiency. This demand was met by introducing the FM service portal (from IWMS) and EMS. Initially the FM portal was implemented in March 2017. The FM portal shown in Figure 21 enabled all KMD employees in Denmark to report faults and errors to the FM department in a more uniform way. The FM portal automatically populates employee information (personal data fields) and includes several predefined fault categories and related fault codes, making employee reporting more standardised and easier to analyse.

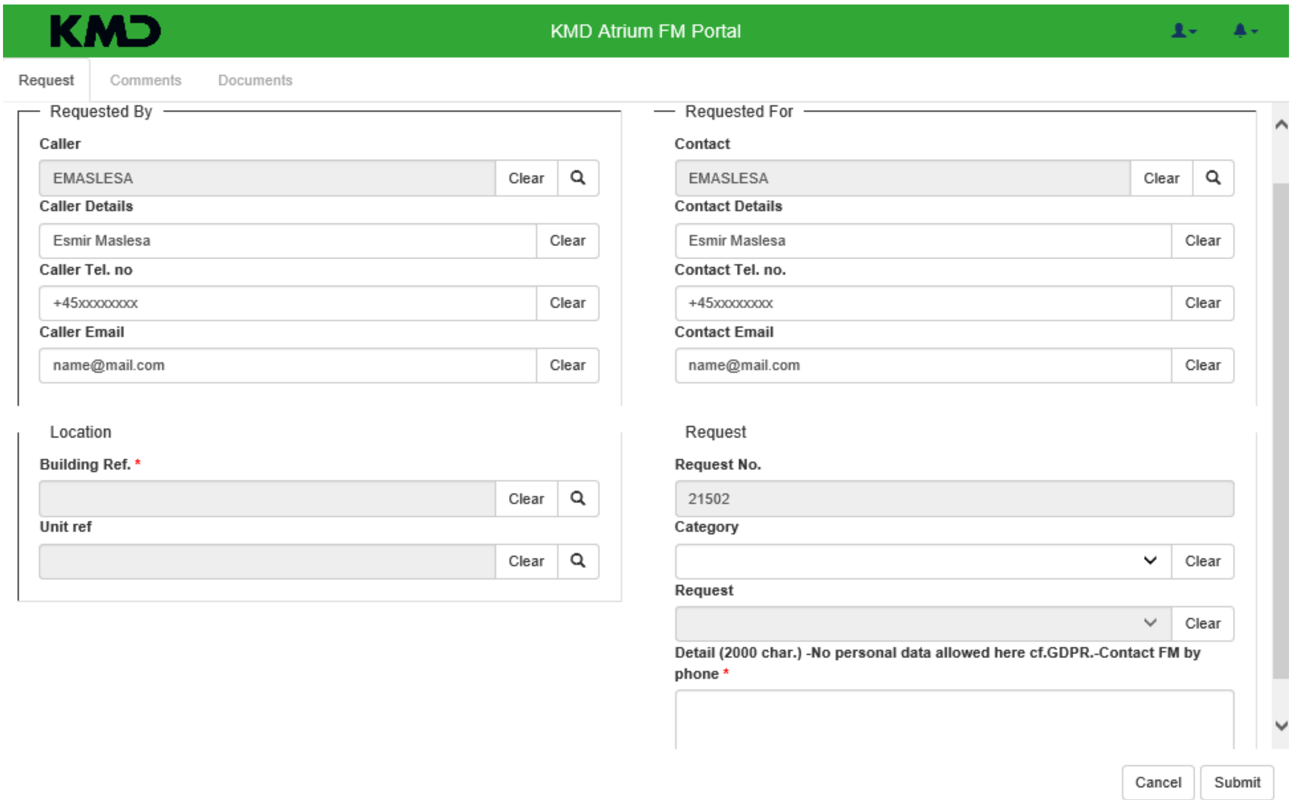

Figure 21: KMD's FM portal. Personal data is automatically populated (anonymised in figure). Fault categories are pre-defined in a drop-down menu under "Category" (Source: KMD Atrium).

During the past twelve months, between 341 (July 2018) and 689 (January 2018) service requests have been reported monthly in the portal. Most of the requests were relating to cleaning and the canteen (interview, FM director), but the portal also includes fault categories related to EBP such as indoor climate, waste management and lighting. According to the FM department, the FM portal creates visibility on fault reporting and work orders that can be used to initiate measures to improve EBP. For example, summer 2018 was one of the warmest in Denmark, which also led to many (several hundred) complaints regarding poor indoor climate in a particular office building that does not have mechanical cooling system. The FM department has collected these data and plans to use them more strategically to argue for a mechanical cooling system to be installed in the building.

The EMS was deployed at the end of 2017, but due to limited FM resources, the implementation is still ongoing. It is now expected to be completed in summer 2019. However, some consumption data is already being reported to EMS. The BMS sends data readings from around seven hundred sub-meters from half of the main buildings in Ballerup to EMS through an interface. The data values are reported to EMS via a file transfer server every hour. Electricity data from the main meters at all KMD locations are automatically reported to EMS from the national datahub. Once fully implemented, EMS is expected to save time on (manual) energy readings, which will become more automated. However, the FM department will continue to use Excel in the future as EMS cannot fulfil their need to be able to benchmark several meters at once or present graphs like Excel. Thus, the consumption data from EMS will be exported and used in Excel for reporting and benchmarking.

4.3. Case III: Postnord Denmark

4.3.1. About Postnord DK

Postnord Denmark (DK) provides postal services to households and businesses in Denmark. Postnord DK is a part of the Nordic postal consortium "Postnord", which also has branches in Finland, Norway and Sweden. Due to decreasing postal demand in Denmark, Postnord DK has had several reorganisations and employment reductions in recent years. Consequently, the property portfolio has also been reduced from 650,000 m^2 in 2012 to approximately 600,000 m^2 in 2017, and the reduction is still ongoing (interview, FM specialist). As part of the reorganisation, in 2015, after more than a hundred years, Postnord DK moved its headquarters from Copenhagen city centre to Amager (Broberg, 2015). Figure 22 and Figure 23 show the old and new headquarters. The company also outsourced all FM-related tasks to an external service provider and now has one FM employee responsible for communication and coordination with the service provider.

Figure 22: The old headquarters in Copenhagen that Postnord has been using since 1912 (Photo: google.dk).

Figure 23: Postnord's new headquarters at Amager (Photo: avcenter.dk).

4.3.2. Managing EBP through IT systems at Postnord DK

Even though most FM services are outsourced, Postnord DK has decided to keep energy management within the organisation, since this is considered as a business-critical area. The production lines handle and distribute letters and packages at several locations across the country, and their efficiency is closely linked to the company's energy management. Postnord DK has been using EMS for energy management for several years in order to monitor and benchmark production line efficiency across its distribution centres. For example, the system monitors hourly electricity consumption by the production lines, as shown in Figure 24.

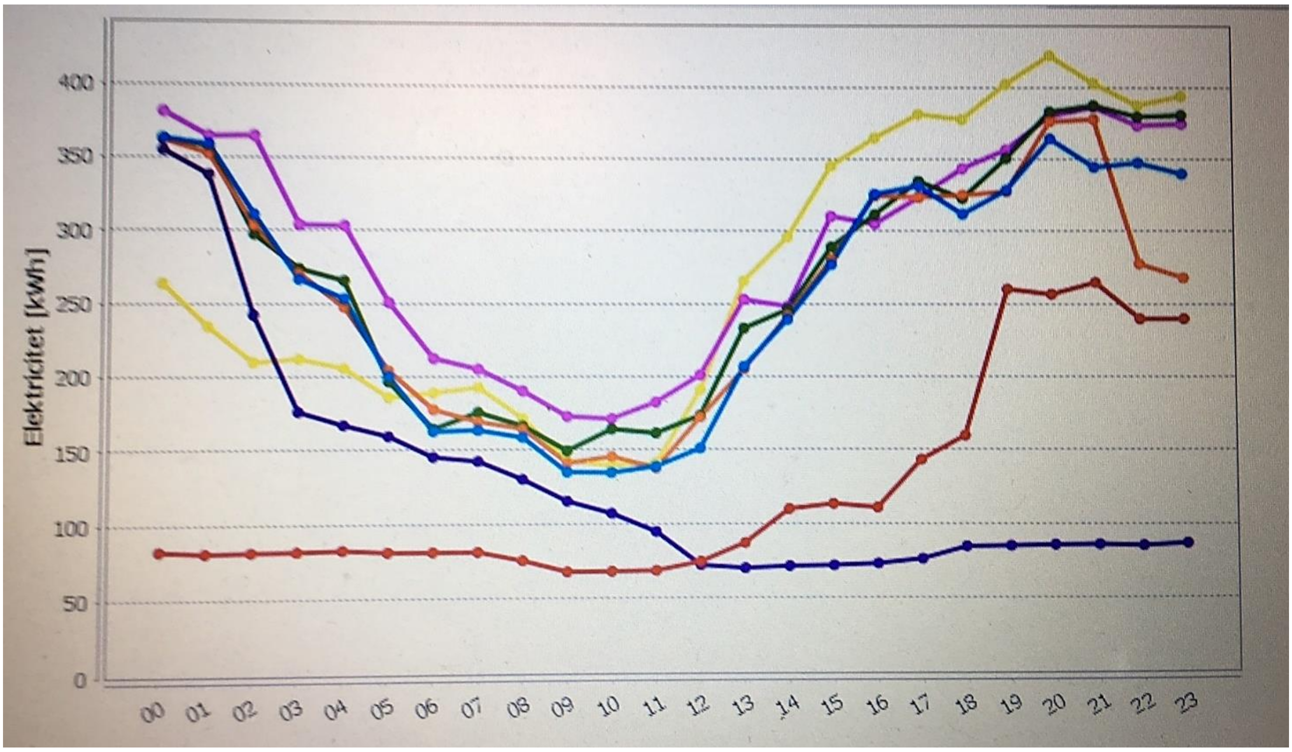

Figure 24: Hourly variations in electricity consumption of a production line at one of Postnord DK's locations. The readings show high consumption in hours 13-05 during week days, and low consumption at weekends. The stand-by consumption at weekends is around 80 kWh (dark blue: Saturday; red: Sunday) (Source: Postnord, KMD EnergyKey).

The EMS feature presented in Figure 24 displays hourly electricity consumption of a production line. The functionality is useful for identifying energy waste as the graph can show much electricy is used for handling the postal products every hour, as well as for stand-by consumption, when the production line is not in use. In this specific case, the stand-by consumption is around 80 kWh. This information is especially useful for facilities managers for further, in-depth analysis of stand-by consumption, to determine potential energy waste during non-operating hours.

The EMS also benchmarks electricity and heating consumption across buildings. In March 2012 Postnord ran a Green Behaviour campaign among approximately 12,000 employees in 224 buildings. During the four weeks of the campaign, total energy consumption was reduced by 19.2%. Data collection and sharp measurements through EMS, targeted information and a competition feature gave employees ownership of the campaign (Energiforum Danmark, 2014). In the campaign, the EMS was used for remote readings (data collection) and visualisation of energy consumption at different locations. In this way, the EMS was used as a trigger for improving environmental building performance, as the system acted as a data platform for establishing the consumption baseline, highlighting the differences in energy consumption between locations and departments, and for benchmarking.

Some activities arising out of a Green Behaviour campaign continued later. For example, monthly energy reports are sent to post district managers regarding developments in energy consumption.

Postnord DK also used EMS to document and visualise the effects of energy renovation projects to top management. For example, an LED lighting project in a distribution centre was expected to reduce monthly electricity consumption by 10%. When the project was completed in August 2016, the effects were instantly visible in EMS, showing that the new lighting was reducing monthly electricity consumption by more than 10%. For example, in September 2016, the consumption was reduced 10,5% and in October 2016 16,8%, when compared with corresponding electricity consumption for the previous year.

4.4. Case IV: Anglia Ruskin University

4.4.1. About Anglia Ruskin University

Anglia Ruskin University (ARU) is an educational institution in the United Kingdom. The university has around 18,000 students and 1,800 staff members at three main campuses: Chelmsford, Cambridge and Peterborough. The university has 191 buildings covering 93,000 m^2 of academic floor space and 26,000 m^2 of residential floor space.

Figure 25: Marconi building at Anglia Ruskin University, Chelmsford, UK (Photo: Author).

As part of an external research stay, the author visited ARU's campuses in Chelmsford (Figure 25) and Cambridge. The research stay took place in April 2018. During the stay the author conducted document studies and two interviews with the FM department. The aim was to reveal, how IT systems are used to manage EBP outside of Denmark.

4.4.2. Managing EBP through IT systems at ARU

The FM department used several IT systems for managing environmental building performance. The main IT system used by a sustainability engineer was BMS. The system was used for energy reporting of electricity and heating consumption and was monitoring more than 50,000 measuring points across the university. The organisation also used EMS for half-hourly energy measurement. The data were used for monitoring and benchmarking energy consumption across the campuses, as well as for strategic reporting. The environmental manager responsible for EBP and CSR reporting was mainly using CAFM for data analysis and reporting.

According to the interviewees (the sustainability engineer and the environmental manager), the current system design had its benefits and limitations. The sustainability engineer alone was responsible for monitoring more than 50,000 measuring points in BMS. Due to the very limited human resources in the organisation, the BMS was neglected in many years, meaning that the data stored in the system did not have great value in many cases. For example, the sustainability engineer showed, how the system still contained data on buildings that were no longer part of the university campus, while data on some specific buildings and measuring points were lacking. The sustainability engineer also explained that in many situations building users would phone him to report issues on HVAC and complain about the poor indoor climate. Consequently, many of the workflows included reactive maintenance, as the BMS was not able to notify failures or predict potential issues due to outdated and inappropriate data.

The FM department used the EMS as an energy-reporting system for benchmarking building performance and for bill validation. Electricity and gas data are automatically sent every half hour from BMS to EMS through an interface, and the readings are displayed in an energy dashboard tool. Water consumption is reported at a higher level, that is, with lower data resolution. The data resolution is closely linked to the financial value of each consumption type. Energy consumption (electricity and heating) was estimated at 2.2 million a year, water consumption at £100,000 a year. According to the environmental manager, these financial costs are the main reason, why the focus is on energy more than on water consumption.

The FM organisation has been using CAFM for seven years and EMS for five years. The organisation uses a three-step model for managing EBP. In the first step, key performance indicators (KPIs) are used for benchmarking energy consumption in EMS. The main KPIs are energy consumption per area (kWh/m^2) and emissions reporting (CO_2/m^2). In the second step, the KPIs are normalized against floor space and the number of staff and students (fulltime employees and students) in CAFM. The last step combines normalized KPIs with financial income at the university level.

The data collected from BMS and EMS are used at monthly management meetings for the energy benchmarking (kWh/m^2) of university buildings. The environmental manager and others use the meetings to determine, which buildings perform the worst and discuss potential areas of investigation to improve performance. Based on their decisions, the areas identified are then monitored weekly or daily in order to obtain more details about energy performance and identify possible measures of improvement.

Anglia Ruskin University, like KMD, is ISO 14001 certified, meaning that the organisation also collects and monitors other data relevant to EBP. For example, Anglia Ruskin Universitycollects waste data. These data are not collected in CAFM, but in Excel. The waste weight data is received monthly from contractors. General waste, waste recycling and food waste are tracked in Excel (tonnes).

5. FINDINGS

This section presents the main research findings from the case studies and highlights the important topics when using IT to manage environmental building performance (EBP). The findings are based on publications P4 and P5, in which different organisations were studied and compared to determine the potential similarities and differences in their IT systems and management of EBP.

5.1. Drivers for IWMS and EMS

Before showing how IT systems can be used to manage EBP, it is important to understand why REM/FM organisations choose to implement new IT systems and what their drivers are. The drivers are in this disseration defined as triggers initiating the intervention (in this case IT implementation) in the organisations, as described in the Value Adding Management model in Section 3.1.2. The research in P4 and P5 determined several drivers for implementing new IT systems within REM/FM organisations.

Hanley and Brake (2016) emphasised that global corporate REM organisations mainly implemented IWMS to reduce costs. However, P4 indicates that Danish public REM organisations might have other reasons for implementing IWMS. The main drivers for implementing IWMS at BYGST were in P4 classified as improving the quality of internal business processes. BYGST wanted to move away from a silo-based organisation and build up a knowledge-based organisation in which employees could use the same core data in carrying out their respective tasks. As such, BYGST case study is a great example of system-thinking approach (Lewis et al. 2010) in which the organisation replaces silo-systems with a more cross-functional system. Some of the main implementation drivers at BYGST were related to data uniformisation, validation and easier data exchange across departments and with external users. Other drivers included faster execution of business processes, time savings and resource optimisation, better interoperability between departments and savings on IT costs.

KMD, the private company, also underwent a major reorganisation of its FM department, resulting in fewer FM personnel. These organisational changes required more efficient workflows and data management and triggered the implementation of IWMS and EMS. Postnord DK has also had several reorganisations in recent years, resulting among other things in a reduced building portfolio and the outsourcing of FM services, though one FM specialist and the EMS were kept in house. The EMS was used by Postnord DK for almost a decade to monitor and benchmark the efficiency of production lines and energy consumption across different locations, indicating a close link between the system and the core business (post distribution). As such, the EMS could not be easily outsourced, as it is considered to be a critical part of Postnord DK's IT infrastructure.

Anglia Ruskin University used several systems for managing environmental building performance: BMS, EMS and CAFM. In this case, BMS was the main system used for managing EBP, while EMS was used for monitoring and reporting. The CAFM system was used at middle management level for strategic reporting through the three-step model.

The implementation of new IT systems at BYGST and KMD has parallels with the concept of business process reengineering (BPR). The triggers for implementing IWMS seem to be the organisational changes in which the IT system is used to support change processes and to deliver new benefits to the organisation. This was particularly visible during the implementation of IWMS at BYGST in which benefit maps were used to visualise the expected benefits of each IWMS module for a specific department. The benefit realisation maps contained information about IT deliveries, expected effects and strategic impacts (goals), as well as about user skills and training, thus highlighting the relationship between the necessary organisational change and the implementation process.

5.2. Implementation process (BYGST)

To deliver the expected benefits, IT systems must be deeply embedded in the organisation's DNA. The field observations during the implementation of IWMS and EMS at BYGST provided a unique insight into implementation processes at a PREM organisation. The implementing process was complex since it impacted on three spheres of innovation (the product, process and organisational spheres) and involved different stakeholders. The product (IWMS) was enhanced during implementation and configured to match BYGST's needs. Vice versa, the internal business processes at BYGST were reviewed and could be changed to match the system's configuration. In the organisational sphere, several notable changes occurred during implementation. For example, BYGST has changed its CEO twice, and some key employees deeply involved in IWMS implementation found new positions outside BYGST. Moreover, BYGST has recently also been given the responsibility for providing FM services to their tenants. Consequently, BYGST needed to allocate resources to developing this business area in parallel with IWMS implementation, and it has also decided to implement the IWMS FM module in 2019.

The implementation process at BYGST included system-thinking as the process was cross-disciplinary and involved different stakeholders. The official implementation team consisted of 35 people with different professional backgrounds, supported by additional personnel as required. During implementation, several team meetings, implementation workshops and implementation meetings were conducted involving different stakeholders. Figure 26 shows one of the implementation workshops at BYGST.

Figure 26: One of the implementation workshops at BYGST including representatives from BYGST, KMD, Trimble and Implement Consulting Group (Photo: Author).

The IT project had an agile implementation approach in which the five IWMS modules were implemented separately, rather than the whole system being implemented at once. The implementation team selected this approach to reduce the risk of critical system failures and ensure a better match between organisational needs and system configuration. ICG estimated that the complete implementation required about 100,000 man-hours, of which 50,000 man-hours were spent by the software providers and the same amount by BYGST and its consultants from ICG (estimates provided by the head of the ICG team at BYGST).

The findings from P3 and P4 indicate that successful implementation can only happen, if the system configuration matches the needs of organisation. The IWMS is not an off-the-shelf solution, but is highly dependent on users' inputs during implementation. On the other hand, REM organisations must at the same time critically review their business processes, for example, through BPR. Implementing IWMS can take several years, which highlights the importance of additional management tools like benefit realisation diagrams for documenting and tracking whether the implementation follows the initial plan and delivers the expected benefits.

IWMS implementation at BYGST has affected all employees working with REM to some extent. This happened through implementation workshops and user training, as well as the compilation of all core data in a single system. P3 and P4 showed that the implementation of IWMS and EMS lead to more coherent workflows with a common basis, but the full impacts are not yet visible, as the entire IT project will be completed in spring 2019.

The findings from P3 and P4 regarding the BYGST implementation process clearly demonstrate that the IT provider and REM organisation must collaborate closely during implementation to ensure a proper system configuration that fulfils the actual needs of the organisation. Furthermore, REM organisations, besides the financial costs, must be prepared to invest time and human resources in the implementation process to achieve the desired results. In the BYGST study, the time investment ratio was estimated at fifty-fifty between the software provider and the customer, highlighting the fact that the implementation process and user training are as important as the software costs. Thus, implementation must include goal setting and user involvement and be able to manage organisational changes. These aspects might be a particular challenge for smaller organisations with limited financial and human resources, as established in cross-case analysis in P5, and they partially explain why it is mainly larger REM organisations that implement IT systems like IWMS.

5.3. Managing EBP through IT systems

The cross-case analysis in P5 found that EBP can be managed through several IT solutions. Table 4 provides an overview of the IT systems used for managing EBP in the organisations studied. The analysis showed that organisations used both "simple" IT systems like Microsoft Excel, the point-systems BMS and EMS, and more advanced system types like CAFM and IWMS for managing EBP.

	BYGST	KMD	Postnord Denmark	Anglia Ruskin University
Organisation type	Governmental real estate agency	Private IT company	Public postal company	Educational institution
Portfolio size (m^2)	4 million	105,000	600,000	119,000
Main IT system(s) for EBP (highest priority first)	EMS IWMS*	MS Excel BMS EMS*	EMS	BMS EMS CAFM
Energy management	YES	YES	YES	YES
Water management	YES	YES	YES	YES
Emissions	YES	YES	YES	YES
Waste management	(YES)	(YES)	(YES)	(YES)
Space management	NO	NO	NO	NO
Building materials	NO	NO	NO	NO
Indoor environmental quality (IEQ)	(YES - BMS)	(YES - BMS)	(YES - BMS)	(YES - BMS)
Reuse potential	NO	(YES)	NO	(YES)

Table 4: The main findings from the cross-case analysis (P5).
**ongoing implementation*

All four organisations were either already using or in the process of implementing EMS. Besides EMS, two Danish organisations (BYGST and KMD), as well as Anglia Ruskin University, used additional IT systems for managing environmental building performance. During the PhD, BYGST implemented four IWMS modules and EMS, and is currently implementing the IWMS Energy module and developing an API between IWMS and EMS for automatic data exchange, all due for deployment in spring 2019. In the future, BYGST plans to combine IWMS and EMS for the strategic reporting of EBP. KMD has been using Excel to manage EBP for many years and has recently decided to automatize data collection of its energy consumption through BMS and EMS. Postnord DK has been using EMS as a stand-alone solution for energy management and emissions reporting for many years.

These above findings show that different IT systems, from simple to advanced, can be used for managing EBP and that the environmental focus is mainly on energy and water management, and emissions reporting. The primarily focus in studied organisations was on electricity, heating and water consumption. Waste was managed by external suppliers that could deliver the data used for strategic reporting. Regarding indoor environmental quality (IEQ), some energy indicators, like indoor temperature, air quality and relative humidity, were monitored and reported through BMS. However, how the various organisations managed IEQ was different, since their building portfolios contained many different buildings of varying age, use type and technical conditions (e.g. natural or mechanical ventilation). Independently of the systems identified in Table

4, ISO 14001-certified organisations (KMD and Anglia Ruskin Unicersity) collected data on reuse potentials such as hazardous materials and waste recycling and used them for CSR reporting.

An in-depth examination of the IT systems revealed that they contained functionalities related to EBP that were not used in the examined case organisations. For example, EMS could offer waste management, but none of the relevant organisations was using this functionality, since the waste data were being provided by external suppliers. IWMS included space management features and could, for example, show how efficiently the building area was being utilised (vacant/occupied area), but this functionality was not in use either.

The identified IT systems also had certain limitations regarding EBP: data and functionalities related to building materials, their properties and lifetimes, as well as the reuse potential of assets, objects and building components in a building portfolio, were not supported by the IT systems covered in this research.

The cross-case analysis indicated two dominant models for managing EBP through IT systems: one based on BMS, the other on EMS software. Table 5 compares the two models and highlights their differences. The main difference is that the data sources are different: the EMS model focuses on consumption meters, while the BMS model is more technical and collects the data from technical installations/HVAC. As the two models each have a different focus within energy management, they should be seen not as competitive, but more as complimentary systems for managing EBP. As observed in studies of Anglia Ruskin University and KMD, the BMS and EMS models can be combined with each other and integrated with other IT systems, which in the end can result in a more holistic overview of environmental building performance.

	BMS	EMS
System type	Single point	Single point
Data source(s)	Technical installations (HVAC) Sensors	Consumption meters
Data capture method	Automatic Manual	Automatic
Data processing	Mostly manual	Automatic
Key features	Indoor comfort (temperature) Air quality Ventilation frequency	Electricity consumption Heating consumption Water consumption
Typical users	Technicians Facilities managers	Energy managers Facilities managers Utility companies End-users (through webtools)

Table 5: The BMS and EMS models as observed through case studies (P5).

The KMD case study revealed that organisations without EMS can combine BMS with other IT systems like Excel for managing EBP. However, the BMS model at KMD seemed to be difficult to manage, as it required many human resources and manual workflows for data collection in Excel, while the EMS model at BYGST provided automated data collection and workflows.

Single-point systems like BMS or EMS have a high degree of customisation for a specific need. They are more suitable to a concrete department's needs (like an energy department), but they also have limited cross-functionality, which is preferable in large REM organisations. Conversely, choosing advanced systems like IWMS may reduce the ability to fulfil all department-specific needs, since all the processes are aggregated into a large IT system. The ability to individualise specific business processes is therefore reduced with an IWMS solution compared to the single-point systems. On the other hand, IWMS can be configured to match the more strategic needs of an organisation. This is especially valuable for larger REM organisations that require a certain level of standardisation across the entire organisation. Furthermore, since IWMS features many cross-functions, the system can be used to replace several single-point systems, resulting in potential savings in IT costs. This situation was observed in energy management at BYGST, in which the old data logger system was replaced by EMS and the upcoming IWMS interface. However, this particular solution has also revealed certain limitations in IWMS. For example, the IWMS Energy module was insufficient to cover all stakeholders' needs for environmental sustainability reporting. The Energy module is therefore supported by a single-point system, namely EMS, which provides deeper insights into the energy management of BYGST's properties.

The identified IT systems (from simple to advanced) cannot improve EBP alone, but they can highlight the potentials for improving EBP though visalisation of performance data on various environmental categories. Figure 27 presents a framework for improving EBP though IT systems and data, as observed through the case studies. The framework is an input-output/outcome model similar to the Value Adding Management model (Jensen and Van der Voordt, 2017) in which organisational interventions are required to add value to the organisation – in this case support improving environmental building performance though IT. The model is integrated with the common quality circle Plan – Do – Check – Act. The input are interventions decided in the Plan phase and completed in the Do phase. In the Check phase it is evaluated to which degree the output in terms of data also represents a positive outcome, for instance visualised by KPIs. In the Act phase the results are analysed, and they can generate new insights that the organisation can use afterwards to initiate further interventions for improving EBP. In this way the model adds value to the organisation as it reduces negative environmental impacts of building operation, which also impacts the bottom line, e.g. through reduced operational costs.

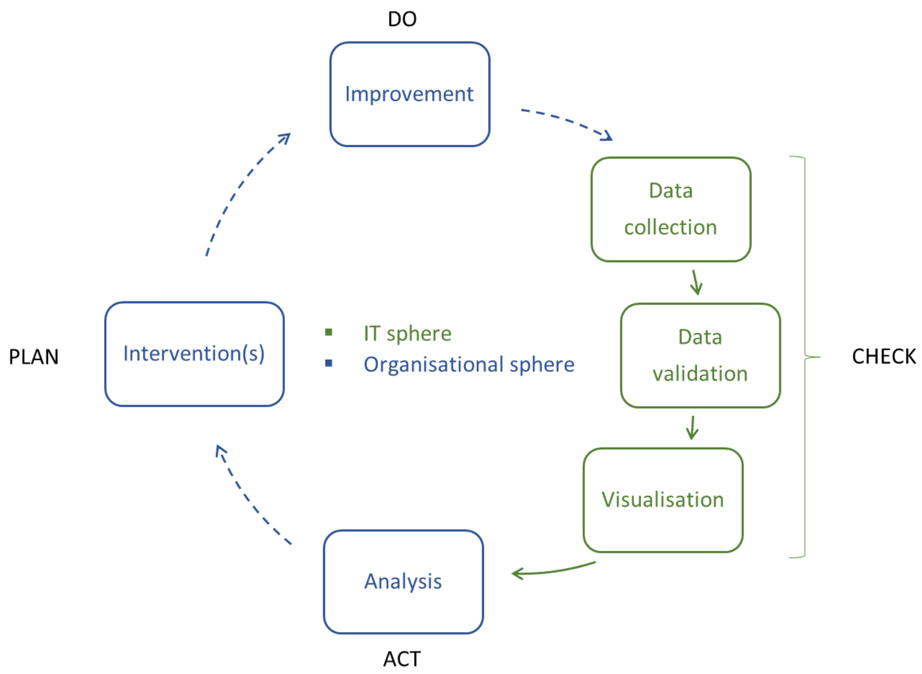

Figure 27: Framework for improving EBP through IT systems and data as observed through case studies.

The important prerequisite for the improvement result, as pointed out by Sandquist (2015), is that the core data and performance data are accurate and realiable. By visualising the performance data through KPIs, as examplified in the case studies of BYGST and Postnord DK, the IT systems can act as triggers for various interventions that improve environmental building performance (EBP). The data outputs from the systems must first be analysed by competent employees, after which specific interventions can be initiated. While the systems can visualise environmental building performance and highlight improvement potentials, it is the organisation's competences and access to the resources that determine the further steps and realistation of specific tasks regarding improvement of EBP. The IT systems can present environmental performance data in different ways towards different stakeholders, but the presented data must be analysed by skilled users that can translate the outputs into specific tasks and projects that can be realised to improve EBP. As disclosed in BYGST study, the energy specialists have access to detailed energy consumption data and other performance data, while remaining employees have access to more aggregated consumption data that can be used for strategic reporting or settlements.

The proper combination of dynamic data in IT systems, as illustrated in P3, can reveal large potentials for energy savings and thereby improvement potentials for EBP. P3 shows that 42% of electricity consumption was used outside of working hours. This information is useful for building operators and facilities managers which afterwards can focus on further analysis of electricity consumption during non-wokring hours, to determine potential energy waste. However, this example highlights both strengths and weaknesses of the IT systems and their outputs. While the systems can provide new insights on energy performance, they lack "human factor" (need human interpretation) and can not explain themselves why the energy consumption is high outside of working hours. Even though the consumption might seem high, there might be reasonable explanations for that: for example, if there are people working outside of predefined working hours, cleaning activities, technical equipment running 24/7, high standby consumption etc. However, these situations need to be examined, to determine if it is the case, or if there is unnecessary energy loss due to errorneous building operation.

At BYGST, the energy specialists use EMS to benchmark energy consumption in office buildings and they use the outputs to provide energy consulting to the tenants. Moreover, the energy specialists use EMS as a dialogue tool with facilities managers and tenants in office buildings, to get deeper understanding of energy performance in each building and to be able to identify energy saving projects.

At Postnord DK, the FM employee uses EMS to monitor and benchmark energy consumption among production lines and distribution centres. Moreover, the EMS is used by external energy consultant providing energy consulting to the company. The external energy consultant uses data from EMS to identify potential energy savings. At the operational level, the consumption data from EMS is used by the district managers to monitor energy consumption at their locations, but they do not have access to the system. The data is provided by the energy consultant or internal FM employee for information and benchmakring purposes.

At KMD, the FM department uses IT systems to monitor and benchmark energy consumption across office locations, data centres and printer centres. Moreover, the company also has a Corporate Social Responsibility (CSR) department in charge of sustainability reporting. The CSR department receives consumption data and consumption reporting from FM department and uses the information for strategic reporting both internally and externally.

At Anglia Ruskin University, the FM department uses consumption data for monitoring, reporting and benchmarking energy consumption across locations, departments, institutes. Moreover, the CSR department uses consumption data from FM department for sustainability reporting. Accounting uses the consumption data for settlements.

The high-resolution data (hourly data) on electricity, heating and water consumption can lead to improved environmental building performance as this data can provide deeper insight on building performance, for example though displaying hourly consumption, highlighting consumption outside of operating hours, and visualising improvement potentials or renovation effects though graphs, charts, dashboards etc. Savings on energy and water consumption reduce impacts on EBP as reduced consumption results in lower resource demands and lower GHG emissions. There is though a difference in data availability and their importance for EBP in Denmark. Currently, electricity consumption has most reliable data quality and data resolution, and its data is easiest to collect, due to the national datahub for electricity consumption. The electricity consumption was considered most important in all four case studies, followed by the heating consumption.

5.4. Dynamic data and LCA modelling

This research distinguishes between IT systems and the data they process. IT systems are regarded as mechanisms for processing different types of data. Data are information with the potential to bring knowledge and value to appropriate organisations. In this research, data are divided into core building data and dynamic data. Dynamic data are performance data that vary over time, for example, consumption data.

The recent implementation of EMS at BYGST has created new possibilities in assessing EBP, since the system provides high-resolution energy consumption data from buildings that were not available previously. Regarding the implementation of EMS, the in-depth study of dynamic data was covered in P6. The research examined the environmental impacts of electricity consumption in eighteen office buildings owned by BYGST. The analysis in P6 revealed that the larger office buildings had higher consumption, while the smaller office buildings had the highest electricity consumption per m^2. When sorted by age, there was no clear correlation between building age, total electricity consumption and consumption per m^2. However, newer buildings generally had higher levels of total electricity consumption, probably due to more electrical equipment. The analysis showed that the data resolution (month/day/hour) for electricity production was important, as it directly influenced the environmental impacts arising from electricity production. P6 showed how the Danish electricity grid evolved from 2012 to 2017 (Figure 28) and revealed an increase in the capacity of wind and solar power.

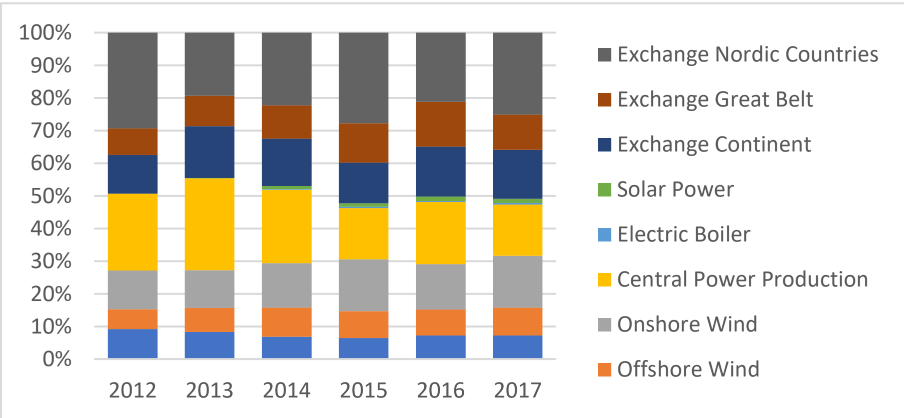

Figure 28: Yearly development of electricity grid in Denmark from 2012-2017 (P6).

In addition, the distribution of electricity production in east and west Denmark respectively (the Great Belt being the dividing line) for June and December 2017 was examined (Figure 29). The Life Cycle Assessment (LCA) analysis showed that renewable energy sources could dramatically reduce the environmental impact per kWh, but that they were still unreliable in respect of their contributions to the grid. The wind power capacity was generally higher in west Denmark, while solar power had notable contributions in June, but not in December.

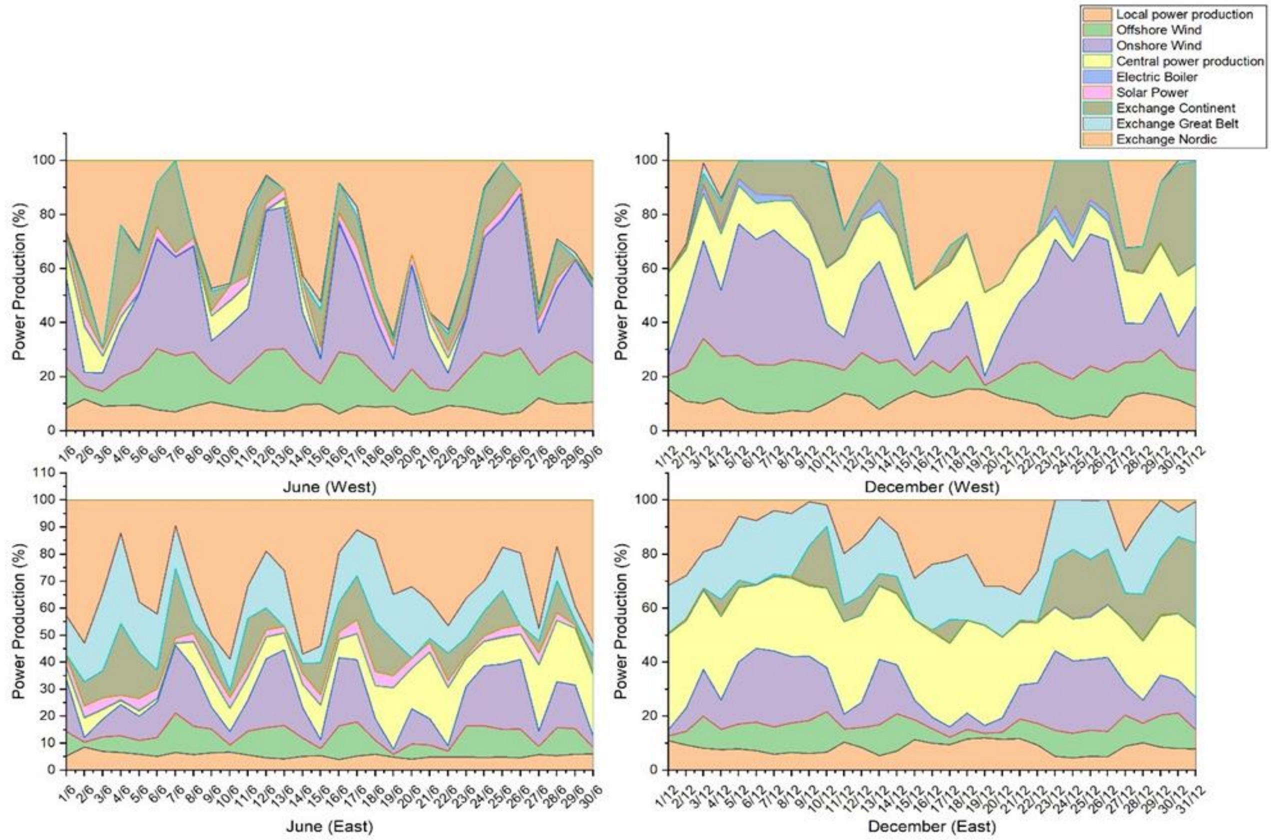

Figure 29: Distribution of electricity consumption in west (top) and east (bottom) Denmark for June and December 2017 (P6).

The findings from Figure 29 showed the difference in electricity composition between the two parts of the country and revealed that electricity composition also varied greatly over the year. These findings were significant, as they highlighted that environmental building performance was not dependent solely on energy consumption, but also on building location (part of the country) and time of the consumption (day/month).

P6 also showed that, even without changing the building area or total electricity demand, the resolutions of dynamic data changed the overall results in the LCA software. However, the differences between the calculated results were not always substantial enough to justify the increased volumes of data and the time required to perform highly detailed analyses.

In LCA, the calculations can be presented as either midpoint or endpoint results. For the midpoint option, the daily data resolutions were the most reasonable solution to recommend in this study. The endpoint impact scores proved to be another story, as every increment in data resolution provided significant changes in results. As a result, the choice of data resolution would impact on the results for any increment used.

5.5. Model development

The overall research findings showed that dynamic data in proper combination with various IT systems can be used by REM and FM organisations for managing and improving EBP. However, the observations from this research led to the identification of several levels for how IT systems and dynamic data can support improving environmental building performance. Based on these findings, a step-by-step model for improving environmental building performance and real estate management by means of IT systems and dynamic data is proposed, inspired by Gartner's market guide for EMS (Gartner, 2017a). The model is presented in Figure 30.

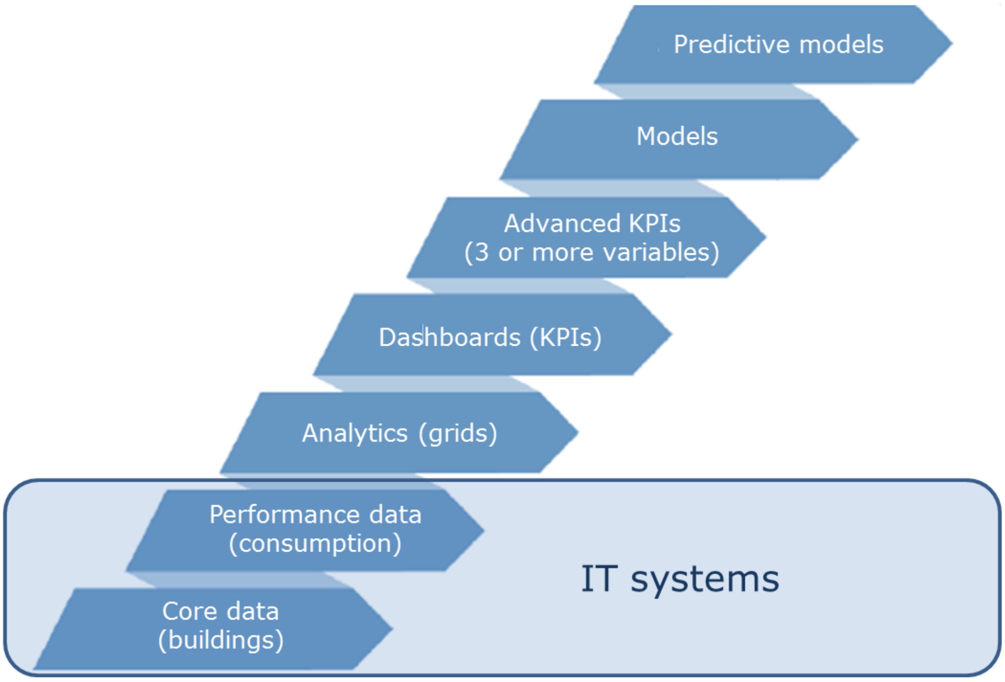

Figure 30: Model for EBP optimisation through IT systems and data.

The IT systems alone cannot improve environmental building performance, but they can be used for managing and highlighting the potentials of improving EBP. To manage environmental building performance (EBP) successfully by using IT systems, the basic data foundation must be in place. This means that the building core data and performance data must be reliable and easily accessible. On the other hand, IT systems must be able to process the data and perform the necessary data analysis in accordance with different stakeholders' needs. Once the basic data and system foundations are in place, organisations can take a stepwise approach to managing EBP, as illustrated in Figure 30. To begin with, the IT systems can be used to combine core data and performance data in "Analytics" to display simple grids and graphs (e.g. energy consumption per building). Later, these data can be combined using simple variables in "Dashboards" to provide quick overviews of selected KPIs (e.g. energy consumption per area). In the next step, several variables can be combined (e.g. energy consumption per area per person) to develop more sophisticated dashboards through "Advanced KPIs". In "Models", large data sets from different sources can be combined to provide a more comprehensive picture of EBP. "Predictive models" consider different scenarios for future building performance and are based on dynamic data from multiple data sources. They can, for example, combine energy consumption and energy production data and indicate, when it is beneficial to use more energy in buildings, or when to save energy, depending on the energy composition profile.

The analysis of IT systems in the studied organisations indicated that advanced IT systems like IWMS can currently manage environmental building performance up to the “Dashboards” level (KPIs) in Figure 30. For example, IWMS can combine different variables to display GHG emissions in a dashboard, as shown in Figure 31. The dashboard shows CO_{2e} emissions per month and indirect GHG emissions that are converted into CO_{2e}. It also shows emissions by source (e.g. commuting, energy purchases, product transport), highlighting commuting and energy purchases as the largest contributors to GHG emissions.

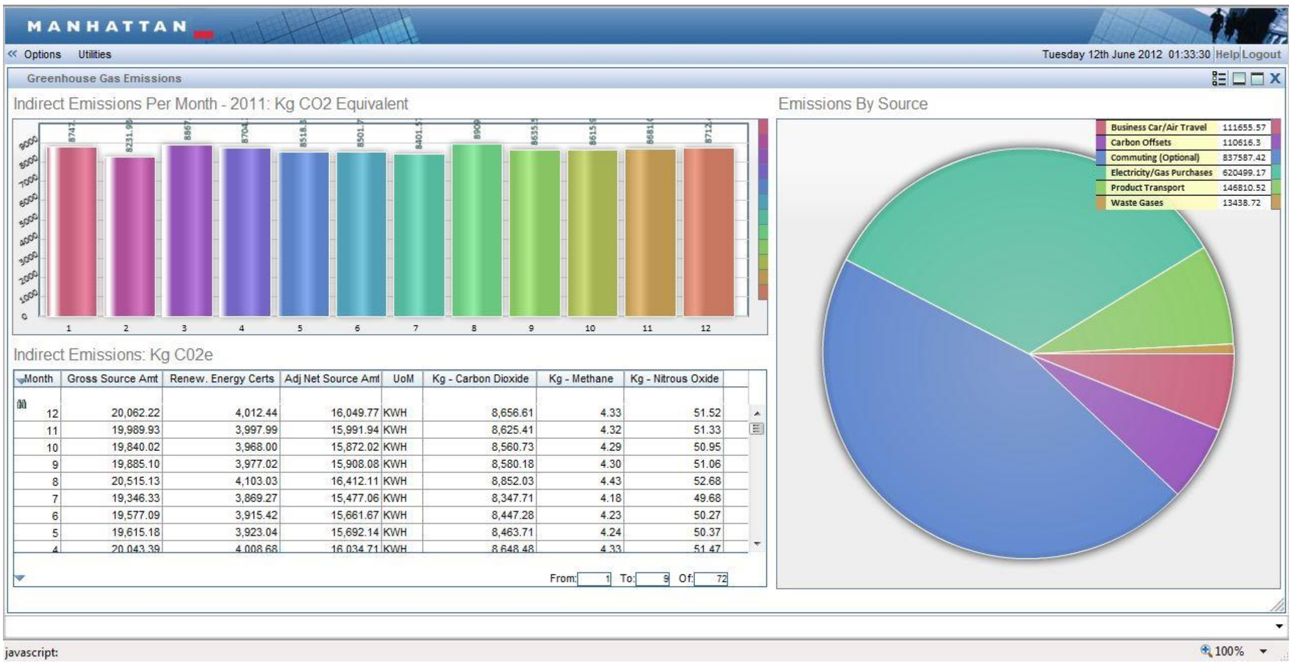

Figure 31: GHG emissions dashboard in IWMS “Manhattan” (Source: Tekla.com).

However, P6 showed the potential for moving up to the “Models” level through a proper combination of IT systems and dynamic data. For example, P6 showed that the appropriate combination of high-resolution consumption data from EMS with the electricity production data (delivered from the national datahub) could provide new insights into the relationship between energy production and energy consumption and their impact on EBP. In a concrete situation, P6 showed that 1 kWh of electricity used in Danish office buildings during the winter could have an impact of up to a factor of two on EBP, when compared with 1 kWh of electricity used during summer season. This finding underlined the importance of dynamic data and highlighted the fact that energy-efficient building operations do not necessarily have to focus on energy savings, but can concentrate rather on proper energy use in accordance with actual building demand.

6. DISCUSSION

6.1. Reflections on research methodology

The methodological approach adopted in this PhD brought both benefits and limitations to the research. In the initial literature review, the final choice of 69 journal papers was the result of a systematic approach applied to 1,125 research papers. Three iterations were applied (on topic-relevance, paper type/journal, and publication period), each iteration reducing the number of relevant papers. However, since only journal papers published from 2010 onwards were considered, relevant research conducted before 2010 was excluded. Furthermore, the literature review considered only peer-reviewed journal papers, without taking other academic papers or practice-oriented research into account.

In case studies, multiple data sources were used to address and deal with credibility, transferability, dependability and confirmability of research findigs. The data were collected through interviews, document studies, field observations and, in the main case (BYGST), also through participation in implementation meetings and workshops. The purpose of using multiple data sources was to enhance research credibility through data triangulation.

The generalisability of the results of this research may be discussed since the research is based on a small sample. This research was limited to four contrasting cases, of which three were from Denmark and were related to KMD's products. The research context was therefore on the Danish REM/FM sector and focused mainly on IWMS and EMS solutions. It would be desirable to have more cases, each covering specific REM/FM organisations (small or large) from either the private or public sector, to draw a better picture of IT system needs across each sector. However, due to time constraints and the nature of IT-implementation projects, which may take several years, the four case studies were considered sufficient for answering the research question and developing a first prototype model of EBP assessment.

Besides generalisability, special attention in this research was paid to interviewer bias. The researcher was an industrial PhD fellow officially employed by KMD and as a "KMD employee" gained access to examples of Danish organisations. Interviewer bias was therefore especially important to address, as the interviewees might have treated the interviewer as a KMD employee rather than a researcher aiming at neutrality. Consequently, the interviewees might attempt to hide some data or present themselves in a more desirable role or situation, which in the end would cause response or interviewee bias.

In the main case study, good relationship with KMD and BYGST brought depth to the study. The researcher was involved in the implementation of IWMS/EMS at BYGST as a part of the implementation team over a long period (two years). As such, the researcher had access to the implementation process and system design documents. The close collaboration with the case-study organisation provided easier access to specific documents and enabled unique insights to be obtained into their working culture, organisational needs and strategic goals with the implementation. Moreover, the researcher was allowed to attend internal KMD/Trimble implementation meetings, implementation meetings and workshops at BYGST, as well as strategic team meetings including all involved stakeholders. However, this valuable research position also entailed the great risk of interviewer bias. Prior to the interview sessions, the researcher spent some time at BYGST as part of KMD's implementation team, which might have caused some interviewer bias among the interviewees. To reduce the risk of interviewer bias in case studies, all ten interview sessions were introduced by the researcher/interviewer clarifying that the session was a part of the PhD research project, and not related to KMD or any of its implementation activities (e.g. at BYGST).

The selection of actual cases was highly determined by the KMD's business activities and closely related to its customers implementing IWMS and EMS. Thus, the research sample is limited and narrowed to a single IT provider in Denmark, except from the additional case from the UK. Being an industrial PhD researcher at KMD also meant that other competitors (e.g. CAFM providers) were reserved in sharing too many details regarding their IT products and customers, as the author was often perceived as a KMD employee rather than a researcher. On the other hand, KMD affiliation provided exclusive access to KMD's customers and their IT systems that normally would not be available for the external researcher. For example, the researcher needed a special safety approval by PET (Danish Security and Intelligence Service) for accessing BYGST's IT systems and working with its confidential data. The researcher was safety-approved as a KMD employee and allowed to access sensitive energy consumption data on governmental buildings. Moreover, the industrial PhD position enabled the researcher to access implementation meetings and workshops at BYGST that were strictly reserved to the implementation team and BYGST's employees, providing unique insights on the implementation process and challenges within the organisation. The researcher was free to decide, which people to interview, and usually selected the persons that were either involved in the implementation or were already using the systems related to the environmental building performance.

As a preparation for the interview sessions, an interview guide with five pages of open-ended questions was drawn up. The interview guide was first presented to the interviewee at the beginning of an interview. The reason for not providing the interview guide in advance was the risk that some interviewees might get scared of the five pages of interview questions and give up in advance. All Danish interviews were recorded, transcribed and sent to the interviewees for comments and validation of the transcription in order to ensure data quality and reliability. The interview transcriptions were later combined with data from document studies and field observations to interpret the results and draw research conclusions. The interviews were not anonymised, but in publications job titles were used to identify the interviewees as they were considered more relevant and appropriate for the research.

The results from the main case study were highly dependent on the implementation process of IWMS and EMS. If the implementation at BYGST had been delayed for some reason (as can happen with complex IT implementation projects), the results would also have been delayed and could affect the research results and development of the model for EBP assessment. In that case, the delay would have been used to study, how REM organisations behave when the implementation of large-scale IT systems is delayed.

6.2. Theoretical framing and practical application

The theoretical framing could not be based on a single theory but needed to combine several theories, because this PhD covered three research fields: REM, IT and EBP. In the research field of REM, definitions of REM, FM, CREM and PREM were provided to highlight how different stakeholders can have different views and approaches to buildings and their management. The definitions were also used to highlight the relationship between REM and FM in Figure 8. Organisational theory and value-adding concepts were considered important for REM, as it was necessary to understand how the organisations examined were configured and to determine their core businesses and value propositions. Without a basic understanding of the sample organisations and their values, it would be difficult to understand, why they chose to implement new IT systems, and what their views were on environmental sustainability. Benefit Realisation Management

(BRM) and Business Process Reengineering (BPR) were considered as appropriate theoretical approaches in the main case study, since the research covered IT drivers (P4), the implementation process (P3) and the added-value/benefits of the new IT systems (P6).

In the research field of IT, theoretical framing focused on IT drivers, the implementation process and the difference between IT systems and data. The PhD distinguished between “IT systems” and “dynamic data”, as these are seen as two different components in the technological sphere. Regarding IT systems, there seems to be solid academic knowledge on well-established IT systems like CMMS and CAFM, research on a more advanced system type like IWMS is more limited. For example, there is no universal definition of IWMS, and while some see it as a “workflow system” (Ebbesen, 2016, p. 42), others refer to it simply as a “CAFM tool” (Pärn et al., 2017, p. 46). Furthermore, workflow systems and facilities intelligence systems are seen as two separate categories of IT systems, both in practice (DFM, 2018) and in research (Figure 1). However, this research has shown how these different IT systems can benefit from each other through better interfacing (e.g. IWMS and EMS), so the question is, why are they not better integrated? In energy management, there are many synergies between BMS, EMS and IWMS, but the question here is, who should initiate (and finance) the integration – customers, or software providers? These specific systems (BMS, EMS and IWMS) cover different aspects of energy management, each having their strengths and weaknesses, but better interoperability could provide new perspectives on managing EBP through IT systems.

Another important aspect when introducing new IT systems in REM/FM organisations is the implementation process. Several studies (Gibler et al., 2010; Hanley and Brake, 2016; GEFMA, 2017) have emphasised that successful IT implementations do not focus solely on acquisition costs but also include people and processes. Implementing IT brings about changes to organisations, impacting both employees and workflows. Thus, change management is an important part of the implementation process, as it combines product (IT system), process (implementation) and people involvement (e.g. user training). Moreover, the transition from silo-thinking to system-thinking, as argued by Lewis et al. (2010) and examined through the case studies of BYGST and KMD, shows that the cross-functional systems like IWMS can increase data quality and enable better interoperability across the organisation.

Environmental building performance (EBP) was covered by means of a systematic literature review (SLR) which identified eight environmental categories that could be used for assessing EBP. These were later used as a reference for determining environmental categories used in practice, as well as in IT systems. The “EBP” research field related to environmental sustainability in buildings, and it was noted that most of the environmental impacts occurred during the building use stage. In relation to this, the research focus on the IWMS and EMS IT systems was considered appropriate as they are used in the stage of building O&M. The research related to EBP (P1 and P2) indicated that certification tools like BREEAM, LEED and DGNB were popular in practice, while LCA was an accepted scientific method for assessing EBP. As part of this PhD, the LCA approach was used in P6, but the question remains, how can LCA become more integrated into REM/FM sector, and why are certification tools used more in practice? Admittedly, LCA is data-demanding and work-intensive, but it can provide new insights and highlight the weakest environmental points in EBP (as shown in P6). It must therefore be asked, who is going to perform the LCA analysis (internal/external), who is going to use the results, and most importantly, for which purpose? It is questionable, how many REM/FM organisations have resources or competences to conduct LCA analysis in-house nowadays. There is already LCA software on the market (e.g. GaBi, SimaPro, openLCA), but it is mainly used by the consulting companies that work with LCA, not by REM or FM organisations. It is therefore more likely that a REM/FM organisation will hire an external LCA company to conduct the analysis than that they themselves will invest their human and financial resources in developing new LCA software and skills. However, incorporation of LCA principles and methods in IT systems that already include features relevant to environmental sustainability (e.g. CAFM and IWMS) could be beneficial for REM and FM in the long term. Whether this is going to happen, and who is going to run this development, remains to be seen.

6.3. Discussion of findings

The research for this PhD covered four aspects related to the coherence of REM, IT and EBP: drivers for IWMS, implementation process (BYGST), managing EBP through IT systems, and dynamic modelling. In the following, research findings and observations regarding each aspect are discussed.

Findings from the literature (e.g. Hanley and Brake, 2016) and the BYGST case study indicated a difference in drivers for IWMS implementation between corporate and public REM organisations. While corporate REM organisations mainly implemented IWMS with a focus on cost reductions, this was not the case at BYGST, which wanted to standardise internal business procedures and strengthen the organisation by implementing IWMS. Similar to BYGST, the drivers for implementing IWMS at KMD were organisational changes in the FM department. The two case studies showed that large IT implementations and system-thinking (Lewis et al., 2010) could be triggered by organisational changes in order to support the achievement of more strategic goals. These findings have parallels with the Business Process Reengineering (BPR) framework (Hviid and Sant, 1994) in which IT is used as a lever for supporting and enabling changes in business procedures. The drivers are not necessarily financial, but can relate to qualitative improvements that ultimately might also affect the bottom line.

In line with the BPR framework, the implementation of IWMS at BYGST had a focus on customer needs and value creation (Kamp et al., 2005; Jensen, 2008) through implementation meetings, workshops and user trainings. Moreover, the Benefit Realisation Management (BRM) framework was used to highlight the benefits each IWMS module should bring to the organisation. In particular this was done by developing benefit maps for each module, as described in Section 4.1.2. Agile project management (Section 3.1.2) was used during implementation in order to embed IWMS modules in the organisation gradually and thus reduce the risk of failure. The number of people involved in the official implementation team reflected the complexity of the implementation. Officially 35 people from four organisations were involved in the implementation, but the number could be more than doubled, if all sub-suppliers and internal BYGST resources were counted. Ensuring optimal collaboration between the four large organisations (BYGST, ICG, KMD and Trimble) included in the implementation was not an easy task from the management perspective, since they all had their business agendas. A lot of effort was therefore invested in dividing the responsibilities and tasks between the parts, as well as in scoping the project. For example, the following issues were discussed: How should the implementation be realised? Who should be involved? When? Who should run change management at BYGST? When should the project be completed? What happens if the implementation is delayed? How much might it cost? Who should pay for requests for changes and potential interfaces? A lot of questions were raised, and they needed to be assessed to ensure successful IWMS implementation at BYGST.

The project complexity was also reflected in the long time it took to complete it (in total more than six years), indicating that the focus should not be on the actual implementation alone. Considerable resources needed to be invested in project preparation to ensure that certain tasks were not lost, misinterpreted or stuck during the actual implementation process. Prior to implementation, BYGST spent two years investigating, what IWMS is, and how it could fit into their organisation. After that, the proof-of-concept (PoC) exercise ran for a year, demonstrating that the system could actually fulfil its requirements as defined by BYGST. These investigations required many internal resources at BYGST. Eventually, after the PoC had been approved by BYGST, actual implementation was initiated.

Since BYGST was the first large PREM organisation in Denmark to implement IWMS, there are some uncertainties related to this case study. It would be relevant to study more IWMS implementations in similar PREM organisations to gain deeper knowledge of the implementation process, implementation time, project management, acquisition costs etc. For example, it would be relevant to examine how many internal resources (man-hours) are required for successful IWMS implementation? Moreover, the full effects of IWMS implementation at BYGST were not covered substantially by this PhD research as implementation is expected to be fully completed in spring 2019, after the PhD dissertation has been submitted. Thus, it might be useful to study the effects of IWMS at BYGST at a later point in time, after the entire system and its interfaces have been deployed and have been used for some time.

The four case studies showed that IT systems and dynamic data can support REM and FM organisations in improving their environmental building performance, but the actual improvement cannot happen solely on the information provided by the systems. The organisations must have resources and capability to translate the information into concrete action points that can be realised to improve environmental building performance. As stated by Dove (1999), knowledge has no value until it is applied, which means that even though the system provides information on environmental building performance, the information must be first translated into usable knowledge, and then interpreted to concrete action points and tasks that can be realised to improve EBP in a certain way. For example, energy consumption data must be monitored and analysed by competent energy managers that are able to read the data and act on the outputs from the system. Based on their interpretations of system outputs, the organisation can choose different inverventions. Other stakeholders may also benefit from the same data, depending on how it is communicated and visualised to them. The new energy management model at BYGST demonstrated how the same consumption data originating from EMS can be used by different stakeholders such as energy managers, end-users and other employees for solving their tasks. Facilities managers may use the data for benchmarking and determining potential energy waste in dialogue with energy managers. The same data can also be communicated to top managers for highlighting potential focus areas and improvement potentials.

The findings from the cross-case analysis showed that different IT systems can be used for managing EBP. The systems might range from simple IT systems like Microsoft Excel over single-point systems like BMS and EMS specialising in energy management to advanced IT systems like CAFM and IWMS. The analysis showed that IT systems were used mainly for monitoring and benchmarking electricity, heating and water consumption, as well as CO_2 emissions, while environmental categories related to building materials and reuse potentials were not covered by the selected systems. On the other hand, some systems could offer functionalities on waste management (EMS) and space management (IWMS), but they were not in use in the selected organisations. Regarding indoor environmental quality, BMS was used in all four organisations to monitor the technical performance of HVAC. The findings from the cross-case analysis were in line with the research findings in P1 and indicated a focus on energy and water management, as well as emissions reporting. But why is the primary focus on energy consumption? Is it because consumption data are easy to collect, or due to other reasons, like their financial value for the organisation? The case studies have shown that not all consumption data are easy to collect in IT systems, as they have different maturity levels (electricity data is the most mature, water consumption data the least). Conversely, there seems to be a strong relationship between importance and quality of data and their financial value. For example, in 2017 KMD spent 23% of its operating budget (excluding rent) on electricity, 5% on heating and around 1% on water consumption. At the same time, the company placed the highest priority on electricity consumption data in their IT systems. Postnord DK also had the highest focus on electricity consumption, followed by heating consumption, in EMS. At ARU, energy consumption (electricity and heating) was estimated at £2.2 million a year, while water consumption was estimated at £100,000 a year. Governmental buildings managed by BYGST spent 1.9 billion DKK on energy consumption in 2017 (excluding water consumption), of which electricity consumption represented ~60% of total consumption costs (1.17 billion DKK).

The importance of consumption data seems to be increasing, as is also indicated by the existence of a national electricity datahub. All utility companies must report high-resolution electricity data to the datahub, from which data can then be directed to IT systems like EMS, after agreement between the utility company and the consumer. This development opens up new possibilities in data harvesting and data analysis that can result in better insights on building performance, as demonstrated in P6. The dynamic LCA modelling in P6 showed that the appropriate combination of electricity production and electricity consumption data could provide new insights on EBP, depending on building location and consumption period (hour). However, there might be challenges in collecting consumption data from the datahub. BYGST spent several months negotiating permissions for data collection in EMS on behalf of their tenants. First, when the agreement between the tenant and BYGST was in place, electricity consumption could be monitored in EMS, and tenants could see their consumption in a webservice. The picture was different for heating consumption data, since there is no national datahub, and because not all heating suppliers were capable of delivering hourly heating data to EMS. Regarding water consumption the situation was even worse, as there are still many manual reading meters across the country, meaning that a lot of data cannot be reported automatically in EMS.

The ability of IT systems to improve EBP is determined by the quality of the data. If the data input is of poor quality (e.g. low resolution/monthly readings), the output will be too. This happens independently of which IT system product is selected. Thus, if the aim is to provide comprehensive insights on EBP, the data input must be valid and be of high quality, otherwise the results might be unreliable, thus providing a misleading picture of the actual building performance.

7. CONCLUSION

7.1. Answering the research question

To answer the research question, four sub-questions were formulated. In the following, the answer to each sub-question is given, followed by the answer to the main research question.

The first sub-question examined which environmental categories were necessary to provide an adequate expression of the EBP. The systematic literature review (SLR) in P1 identified eight environmental categories for managing EBP and found LCA to be the most appropriate scientific method for quantifying EBP. Furthermore, the SLR identified research gaps in environmental categories and revealed that researchers were mainly focusing on energy, water and GHG emissions categories. In addition, P2 provided more research-based knowledge on certification tools and methods for quantifying environmental building performance.

The second sub-question was answered through case studies of different REM/FM organisations to determine what dynamic data were available in IWMS and EMS, and how they could be applied to the environmental categories identified in the first sub-question. The case studies of BYGST, KMD, Postnord DK and ARU published in P3 – P5 revealed that dynamic data used in IWMS and EMS mostly related to energy, water and GHG emissions categories. The findings from the case studies drew parallels with SLR, as identical environmental categories were mostly used in practice, indicating large improvement potentials in both research and practice. Moreover, the case studies revealed that the IT systems could offer additional features related to EBP, but that the selected organisations were not using them. The case studies also revealed that IWMS and EMS lacked features on building materials and recycling potentials, while indoor environmental quality was strictly covered through BMS solutions.

The more general study of the IT systems IWMS and EMS was covered in the third sub-question. Research publications P3 – P4 concluded that the implementation drivers for new IT systems in REM and FM organisations were closely related to organisational changes and highlighted the fact that IT systems must deliver organisational benefits (not necessarily financial ones) to their organisations to be considered successful. While Hanley and Brake (2016) indicated that corporate REM organisations mainly implemented IWMS with focus on cost reductions, P4 showed that public REM organisations might have other reasons for implementing IWMS. The main drivers found in P4, in order of priority, were: data standardisation, validation and exchange; faster execution of business processes; time savings and resource optimisation; better operability between departments; and savings on IT costs. Furthermore, the findings from this PhD study indicate that IWMS is mostly suitable for REM/FM organisations with many human resources, as a lot of time is required for successful implementation. On the other hand, REM/FM organisations with a limited number of human resources can use point-systems (silo-systems) for solving specific tasks. However, these silo-systems bring certain limitations regarding data exchange and workflow efficiency when compared with advanced systems like IWMS, as they lack cross-functional features that REM and FM organisations often demand.

The fourth sub-question studied the benefits of IWMS and EMS implementation for environmental building performance and thereby also real estate management. The case studies and cross-case analysis have shown which benefits IWMS and EMS implementation can bring to REM and FM organisations. Research publication P3 showed that the implementation of IWMS and EMS at BYGST brought several benefits to energy management and thereby also real estate management in the form of standardisation of workflows, valid consumption data, better customer service, and even led to energy savings in some office buildings. The implementation of IWMS at KMD showed that the new FM portal brought easier and more uniform data collection regarding failure reporting on building performance. This data can be used for documenting performance issues and for strategic (e.g. CSR) reporting in the organisation. Furthermore, the implementation of EMS at KMD is expected to bring further benefits to the organisation, as the EMS will automatise data collection and thus provide time savings, increase data resolution (from monthly to hourly readings) and increase data reliability (consumption data provided by the utility companies). Postnord DK already used EMS for several years, providing several benefits: energy monitoring and benchmarking across buildings and production lines, documenting results of energy renovations, and as a data platform in the energy savning campaign. Anglia Ruskin University used a three-step model for managing environmental building performance through several IT systems. Energy consumption was first benchmarked in EMS, and then normalised against floor space and number of full-time employees and students in CAFM. The last step combined normalised KPIs from CAFM with financial income at the strategic (university) level. Furthermore, P6 studied the potential benefits of the dynamic data provided by EMS. The LCA study in P6 highlighted some of the future potentials that high-resolution data could produce in assessing environmental building performance. The research concluded that energy management should not focus solely on energy consumption, but also consider energy sources (e.g. renewable/non-renewable ratio).

Based on the research findings from the four sub-questions, the answer to the main research question of the PhD thesis (*How can IT systems and dynamic data support improving environmental building performance, and thereby also real estate management?*) reads as follows:

IT systems like IWMS and EMS can support improving environmental building performance, and thereby also real estate management, as they provide automated, unified and streamlined workflows related to building core data and performance data harvesting, processing, monitoring, reporting and benchmarking. Furthermore, IWMS provides configurable modules and cross-functionalities and thus supports system-thinking. The actual improvement results depend highly on organisational capabilities and the ability of executing improvement tasks. The IT systems and dynamic data cannot improve environmental building performance alone, but they can be used as triggers for interventions that can lead to improved environmental building performance. Through data collection, analysis and visualisation, the IT systems can highlight the potential focus areas of improvement, that REM and FM organisations must address subsequently.

In this research the drivers for implementing IT systems IWMS and EMS were identified as the organisational changes that are closely linked to business process reengineering and benefit realisation management. The main case study showed that the necessary quality improvements across the organisation might be the trigger for implementing advanced IT systems like IWMS in public REM organisations. The main case study also showed transition from silo-thinking to system-thinking in which several point-systems were replaced by IWMS. This development was deeply anchored in the organisational change process from the beginning as the strategic goal of IWMS implementation was to create “the system” relying on a common data platform which could provide more standardised workflows and functionalities across departments. Also other case studies (KMD and Anglia Ruskin University) showed trends towards system-thinking, but they concurrently highlighted some of the important issues that need to be addressed on the way, e.g. the availability of human resources during the implementation, as well as an access to competent employees that can operate the systems afterwards. Thus, the transition to system-thinking can be time demanding and require many human resources, but the results, as demonstrated through the case studies, can be beneficial in the long term.

The cross-case analysis demonstrated that different IT systems can be used for managing environmental building performance and thereby also REM. Furthermore, the analysis has identified two models of how IT systems and dynamic data can support improving EBP: BMS and EMS. These two models should not necessarily be perceived as competitive, but more as complementary, since they focus on different aspects of EBP. Examining how BMS and EMS models can become more integrated would therefore be beneficial for future management of EBP though IT systems.

The case studies established that environmental building performance (environmental sustainability) does not in itself initiate the implementation of new IT systems. Instead it is mainly strategic, organisational changes that initiate new system implementations in REM/FM organisations. Regarding data collection within EBP, it is mostly electricity, heating and water consumption data that are collected, down to hourly or half-hourly values. This consumption data has large importance for environmental building performance, but there is still a lot of place for improvement within other identified environmental categories from systematic literature review. The energy, water and emissions categories are attractive to monitor and benchmark, partly because of the current global trends in sustainable development, but mostly due to financial incentives. Today, changes in energy consumption are visible almost immediately, having a direct financial effect already from day one. Consumption data has thefore high financial value to top management as it affects operational costs, and thereby also bottom line.

Electricity data in particular seem to be valuable to REM/FM organisations nowadays. Currently high-resolution electricity data are available in Denmark through a national datahub, but there are still no national datahubs for heating or water consumption. Electricity data can therefore automatically be provided to compatible IT systems by the utility companies, while access to high-resolution heating and water consumption data depends more on the local utility companies and might to be limited due to their stage of technological development. Thus, there is still place for improvement regarding access to more dynamic data on heating and water consumption.

The study of dynamic LCA modelling has demonstrated, how IT systems and dynamic data can be used for managing EBP and has identified future potentials within this business area. Combining energy production and energy consumption data in IT systems can soon be used to create a more comprehensive picture of environmental building performance and to develop predictive models of when to reduce or even increase energy consumption.

7.2. Contributions and research limitations

The research for this PhD makes several scientific and practical contributions, which are presented in the following subsections.

7.2.1. Scientific contribution

The six research papers (P1-P6) published as part of the PhD contributed new knowledge in the following research fields: environmental building performance, IT in REM/FM, and real estate management/facilities management. The contribution of each research paper to the selected research fields is shown in Figure 32.

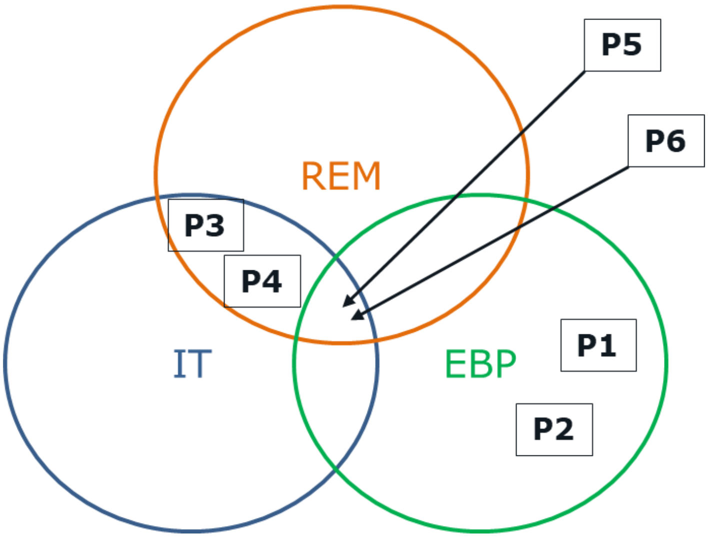

Figure 32: Scientific contributions of the PhD.

Research papers P1 and P2 contributed new scientific knowledge on environmental building performance and identified research gaps within this field. Research publication P3 studied the relationship between IT and REM organisations. P4 examined the IWMS drivers in REM and developed new scientific knowledge on the intersecting fields between IT and REM. P5 investigated the EBP in four different organisations and covered the research topics relating to REM, IT and EBP. P6 made an exceptional research contribution to the issue dynamic LCA modelling by combining high-resolution consumption data from EMS with high-resolution energy production data from the national datahub.

P3-P4-P5 provided case studies of IT systems and implementations in FM and covered thereby some of the research gaps indentifed by Ebbesen (2015) regarding lack of case studies within IT in FM. The four case studies covered by this PhD showed how IT can bring various benefits to REM and FM organisations regarding environmental building performance and supported Ebbesen's conclusion that IT adds value to FM.

While Hanley and Brake (2016) mainly studied IWMS within corporate REM organisations, this PhD primarly focused on the role of IWMS in a public REM organisation. Thus, this PhD brought new research perspective on IWMS as the project studied the implementation drivers for IWMS (P4), and the implementation benefits of IWMS (P3). P3 provided concrete examples of the implementation benefits such as data standardisation and workflow unification. P4 highligthed the challenges of silo-thinking and argued for the system-thinking approach when implementing IT in REM, and thereby strengthened earlier findings by Lewis et al. (2010). In addition, P5 highlighted the similarities and differences between IT systems used by case organisations, their strengths and weaknesses, and suggested two models for managing environmental building performance thorug IT: one based on EMS, another on BMS solution.

P6 showed the environmental trade-offs between electricity consumption and production and highlighted new potentials of combining high-resoultion data in dynamic modelling. The research brought new scientific contribution regarding environmental sustainability of buildings as it pointed out the variations in environmental impacts from electricity consumption throughout the year.

By introducing the technological (IT) aspect into the research, this PhD has uncovered new scientific knowledge within the area of environmental sustainability, clarifying how different IT systems can be used to manage and improve EBP.

7.2.2. Practical contribution

Besides its scientific contribution, the research made several contributions that may be useful in practice. The PhD studied four REM/FM organisations and revealed some of the challenges different organisations might face in implementing new IT systems. Furthermore, the research presented new, research-based knowledge regarding IWMS, a relatively new REM/FM system type on the Danish market. As BYGST was the first public REM organisation in Denmark to introduce IWMS, the findings of this PhD might be beneficial for other Danish/Nordic (P)REM organisations considering implementing IWMS.

Based on the research findings and practical observations, the PhD proposes a model for EBP optimisation through IT systems. The model is inspired by Gartner's guide for EMS, but it also reflects the findings and potentials identified through this research. The model can be used in practice by relevant REM/FM organisations that want to manage and improve EBP through IT. However, it must be pointed out that the model can not improve EBP on its own – it is the organisational competences and skills that determine concrete actions and interventions which can lead to improved EBP.

7.2.3. Overall research contribution

The scientific and practical contributions of this PhD can be combined to form an overall research contribution, as shown in Figure 33. Initially the PhD project created new scientific knowledge on environmental sustainability through two academic publications (P1-P2). The PhD also contributed new knowledge on IT systems in REM/FM, particularly IWMS, and their importance for environmental building performance (EBP). Ultimately, the PhD proposed a new model for managing and supporting EBP through IT systems and highlighted the future potential of dynamic data through dynamic LCA modelling.

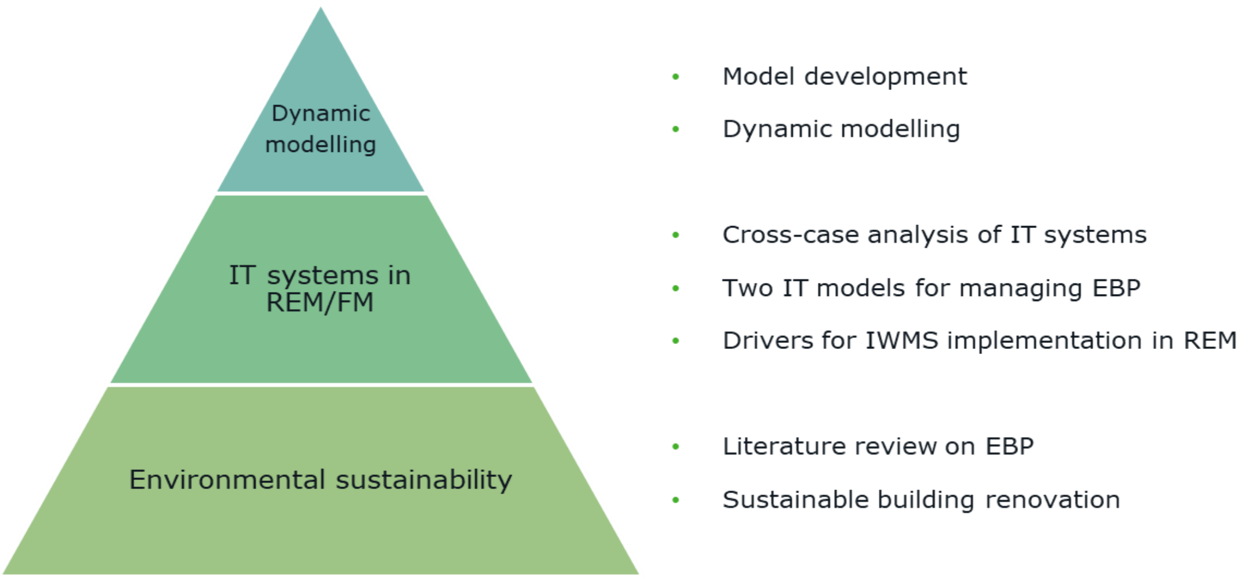

Figure 33: Overall research contribution of the PhD.

7.2.4. Research limitations

This industrial PhD has examined how specific IT systems and dynamic data can support improving REM and EBP. The research context was the Danish REM/FM sector, and the research was conducted in close collaboration with the IT company KMD. As such, the research was limited to specific IT systems used in Denmark. The research was mostly focused on the IWMS and EMS IT systems provided by KMD (except the UK case), as working with the company enabled easier access to the organisations that used its IT systems. This was particularly valuable in respect of the main case study, BYGST, in which the researcher gained unique access to the implementation of IWMS and EMS in a public REM organisation. However, this comprehensive case study revealed that implementing IWMS is complex and can run over several years, resulting in large research demands and partially explaining why there is limited research on IWMS. The focus on IWMS also placed research limitations on studies of other relevant IT systems, like CAFM, which are more widespread on the market, but also better covered in research. Moreover, this PhD did not study other public REM organisations, like municipalities and Danish regions (responsible for hospitals operation and management), or large corporate REM organisations, to determine how they use IT systems to manage EBP.

7.3. Recommendations for further research

The research covered in this PhD showed how certain specific IT systems can support improving environmental building performance and real estate management. During the project, many research ideas were created, and potential research topics identified, but due to the time constraints of a PhD and the research limitations described in the previous section, not all topics have been fully covered by this PhD. Thus, this thesis suggests some of the following topics for further research:

- IT systems and their suitability for different REM/FM organisations. This PhD mainly focused on IWMS, but which organisations use Ticket management, CMMS and CAFM, and for what purpose? It would be helpful to have an overview (guide) of which IT system type is the most suitable for a particular REM/FM organisation type, based on parameters like real estate portfolio size, ownership type, and the availablity of human, as well as financial resources.

- This PhD examined a single case of IWMS implementation in Denmark, but there is a need for more case studies, both in Denmark and in other countries, to determine the more universal strengths and weaknesses of IWMS across different REM organisations.

- The eight environmental categories identified in the systematic literature review were not all adequately covered in practice, partly due to the missing functionalities in IT systems, but also because of the missing demand from the organisations studied. Thus, examining how more environmental categories can be integrated and combined in IT systems is suggested. For example, research on integrating BMS, EMS and IWMS would be beneficial for environmental building performance, as several environmental categories could be centralised in a single system.
- The model for improving environmental building performance through IT systems and data, as proposed in Section 5.5, needs further testing and validatation. The model highlighted current and potential possibilities for improving environmental building performance through IT systems and data. Further research can examine how REM/FM organisations can move upwards in the model to improve management of environmental building performance through IT systems and data.

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APPENDICES

Appendix A: Publications

Author's contributions to Papers 1 – 6:

Paper 1: Main author. The author of this PhD dissertation was responsible for defining the research topic and collecting, analysing and interpreting the research data. Most of the paper was written by the author, with valuable comments and feedback from the co-authors.

Paper 2: Second author. The author was responsible for answering two research questions (questions 7 and 8) and wrote sections 2.7 and 2.8. The author also reviewed and commented on the other sections and suggested improvements.

Paper 3: Main author. The research topic was defined with the co-author. The author was responsible for collecting, analysing and interpreting the research data. Most of the paper was written by the author, with valuable comments and feedback from the co-author.

Paper 4: Main author. The author was responsible for defining the research topic and collecting, analysing and interpreting the research data. Most of the paper was written by the author, with valuable comments and feedback from the co-author.

Paper 5: Main author. The author was responsible for defining the research topic and collecting, analysing and interpreting the research data. Most of the paper was written by the author, with valuable comments and feedback from the co-author.

Paper 6: Second author. The author was co-supervisor of the Master's thesis project that resulted in this publication. The author was responsible for the collection of data from BYGST and the interpretation of LCA results. The author contributed by formulating the research topic and defining the research methods. Furthermore, the author provided ongoing feedback on the article and made a substantial contribution to its revision.

PAPER 1

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Indicators for quantifying environmental building performance: A systematic literature review

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ABSTRACT

Buildings as products are complex structures with a long service life compared to most other products and they induce considerable environmental impacts throughout their life cycle. The Environmental Building Performance (EBP) depends on attributes like building design, selection of building materials, building location, as well as operation and maintenance. This article provides the accumulated scientific knowledge on how to quantify EBP by a systematic literature review. Such knowledge is valuable for decision-makers and facilities managers in the process of implementing an environmental strategy and focusing on improving EBP. The review includes 69 articles that cover three research topics relating to EBP: I) indicator categories, II) building types and III) assessment methods. The results show that the environmental impacts are higher for non-residential buildings, and that the building use stage has significantly higher environmental impacts than the other stages. Relating to that, the article identifies eight main categories for quantifying EBP and discusses two methods for assessing EBP.

1. Introduction

The building sector is one of the most resource consuming sectors. The buildings and building construction sector combined are responsible for 36% of global final energy consumption and nearly 40% of total CO_2 emissions [1]. Furthermore, the construction and use of buildings in the EU account for about 33% of water consumption, 33% of waste generation, and more than 30–50% of total material use, depending on the material type [2,3]. In recent years, global use of energy in buildings has grown by 1% per year and global building-related CO_2 emissions continue to rise by nearly 1% per year [1]. Nevertheless, the interest in sustainable development and building performance has been on the agenda since the early 1960's. Nowadays we see concepts and developments like smart buildings, intelligent buildings, green buildings and sustainable buildings, trying to improve the building performance and reduce the negative environmental impacts from the buildings. The overall goal is to create high-performance buildings that accommodate different aspects of sustainability through their life cycle [4]. Some aspects relate directly to the environmental performance, but there are also economic (operational cost, rental cost, asset value) and social (safety, security, accessibility) aspects that must be taken into account to address all relevant building performance assessment dimensions. Even though EBP focuses on environmental dimension of sustainability, it still has strong ties to economic and social sustainability dimensions through e.g. operational costs and indoor climate quality affecting building users' health. The main drivers for optimising EBP are increased focus on climate change related impacts and building energy efficiency, but also economic considerations such as cost reductions on building operation and maintenance (O&M) activities play a role.

The relationship between building life cycle (design/construction/use/end of life stage) and environmental impacts encompasses high complexity since decisions made in the early design stage combined with external parameters like building location (country) and energy supply type (renewable/non-renewable), and later quality of construction work, affect the following impacts from the use and end of life stage.

Studies on building performance in facilities management (FM) have recently been conducted by Ebbesen [5] and Nielsen et al. [6]. However, these articles are lacking a comprehensive identification of studies focusing on indicators for quantifying EBP. Defining specific indicators enables measurement and analysis of actual building performance and provides possibility to benchmark building performance across property portfolio. At the same time, indicators put limits on measurements since each of them focuses on a specific impact parameter, making it alone insufficient to provide a more holistic performance analysis. To resolve this conflict, similar indicators are often grouped into categories that can provide a more general picture of

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building performance within the given context. This article examines which indicator categories are most commonly used for quantifying EBP. Additionally, the article examines whether residential or non-residential buildings have the largest environmental impacts, and which methods are usually applied for assessing EBP.

2. Method

The article at hand aims to provide the accumulated scientific knowledge on how to quantify EBP. To reach the goal, a systematic literature review (SLR) was conducted according to the criteria presented in Okoli & Schabram [7]. A SLR was chosen as research method for analysing the body of knowledge and identifying potential research gaps. The literature was reviewed to identify main building environmental indicator categories and their role in relation to the whole life cycle of buildings. A SLR includes four stages with eight underlying steps: Planning stage (purpose and protocol), Selection stage (literature search and screening), Extraction stage (quality appraisal and data extraction), and Execution stage (analysis and findings, and writing the review).

In the planning stage, the purpose of the literature review was defined as: Identifying indicators and methods for quantifying EBP and determining which building types have the largest environmental impacts. Here, the authors also agreed on a common protocol regarding review procedure including identifying relevant research databases and key words for the study.

In the selection stage, the literature search was conducted using 5 research databases (DTU FindIt, Google Scholar, ScienceDirect, Scopus, Web of Science). The literature search on key words "building environmental indicator" returned 1125 research articles from 12 international journals. To reduce the amount of results, the scope was further limited in terms of time and topic relevance. The time limitation (2010–2017) was introduced to ensure focus on more recent research, and since the study focuses on buildings, only articles relating to the building sector were considered topic relevant. Introduction of time limitation and topic relevance criteria reduced the number of initially relevant articles to 107 and excluded 4 journals. The subsequent screening of all 107 articles (mainly abstracts) eventually yielded 69 articles on building environmental indicators. These 69 articles (Appendix A) constitute the data set of the study.

In the extraction stage, quality appraisal and data extraction from data set was conducted. The data set was categorised in 5 research areas for determination of which building types induce the largest environmental impacts: residential buildings, non-residential buildings, residential and non-residential buildings combined, buildings in general, and other building-related articles.

The choice of research method entails both benefits and limitations to the article. The method entails review of peer-reviewed research articles with focus on EBP, but also ignores relevant research conducted before 2010. Based on the analysis and findings from the execution stage, the work article identifies indicators and methods for quantifying EBP, determines which building types have largest environmental impacts and discloses several research gaps for further studies.

3. Theory

A building is a combination of components that each induce a set of impacts on the environment. Since a building can be much more complex than the sum of its components, a building should be considered as a unique entity with the main purpose/function to provide occupants with suitable comfort conditions, with a low amount of energy consumption and with a limited impact on the environment [8].

3.1. Building performance and environment

The interest in quantifying relationships between building performance and environmental impacts emerged already in the early 1960's [9]. Building performance assessment has focus on the behaviour of a building under actual conditions of operation. Building performance assessment is seen as a mean to ensure that a building and its parts meets specific building requirements, and so determine the 'building quality' according to specific assessment criteria [10]. Hence, the assessment of building performance during operation is also used for evaluating the building quality. However, building performance is a complex term because the lack of consensus on what constitutes building performance, covering the overlapping dimensions of social, economic, environmental and technological factors [11]. In the facilities management sector, the European standard EN 15221-7 defines guidelines for performance benchmarking and provides a range of key indicators to identify areas in which there might be a need to improve performance.

Environmental Building Performance (EBP) focuses particularly on environmental impacts from buildings induced during their life cycle. Environmental impacts of buildings are typically summarized in two impact groups: embodied impacts (i.e., impacts embodied in the constructed building) and operational impacts (i.e., impacts occurring over the "active" service life and hence during use of the building) [12,13]. The environmental building performance depends on attributes such as building design, selection of building materials, quality of the construction work, building location, choice of energy supply source, and O&M activities [14,15].

Reducing total environmental impacts from a building life cycle is not an easy task, partly because of abovementioned attributes, but also due to the risk of burden shifting that can transfer negative impacts from one building stage to the other. For example, to reduce operational impacts, one can choose to install more thermal insulation or use triple-glazed instead of double-glazed windows, but then again, these solutions will increase embodied impacts since more materials are used for constructing the building.

Once designed and built, it is not easy to change environmentally impactful decisions made in relation to the building design such as building orientation, window-to-wall ratio, and Heating, Ventilation, and Air Conditioning (HVAC) system [16]. The processes used to O&M activities have an even larger cost and environmental impact than the design and construction process [4,17]. Appropriate building life cycle prediction is therefore an important topic for EBP. Cabeza et al. [18] note that in research, the reference study period ranges between 10 and 100 years, with the majority of articles considering 50 years as reference study period for a building life cycle. Grant et al. [19] argue that study period assumptions contribute significantly to expected environmental impacts, by as much as 4–25% depending on the impact category. These claims are also supported by the comparative study of office buildings in Europe and the United States, wherein maintenance impacts comprised 4–15% of the total impact [20]. Another comparative study of nine building envelope systems concludes that maintenance related impacts may range between 2% and 55% of the total life cycle impact, depending on the estimated service life, the estimated maintenance regime, and the frequency and intensity of replacement [19].

3.2. Environmental building performance indicators

The evaluation of EBP is usually assessed through Key Performance Indicators (KPIs) grouped into several categories allowing for comparison of different design solutions and monitoring of actual building performance during operation [10]. Such indicators are used to provide aggregated information about a phenomenon in a clear and efficient way [21]. The purpose of an indicator system is "*to provide a measure of current performance, a clear statement of what might be achieved in terms of future performance targets and a yardstick for measurement of progress along the way*" [11]. The use of KPIs and benchmarking is fundamental to any improvement strategy as KPIs reflect a project's goals and provide means for the measurement and management of the progress towards those goals for further learning and improvement [22].

In facilities management, KPIs are popular as they are suitable for monitoring and controlling desired outcomes of existing buildings. KPIs help the FM organisations to focus on potential benefits in relation to the resources spent [23]. However, there is an ongoing debate about what type of KPIs to select and what they are in fact quantifying. For example, there is a vigorous discussion on whether UNEP Benchmarking Think Tank Index measures environmental performance, sustainable performance, service performance (e.g. durability/adaptability) or energy performance [24].

Another issue is selecting the appropriate number of performance indicators. Selecting a single indicator makes the decision easier, but it can also mean a loss of information. On the other hand, a large set of indicators can limit comprehension and the relative importance of each indicator [25]. Thus, defining the appropriate number of effective indicators is important since the quantitative performance results are influenced by the list of indicators. Ideally, there should be a limited number of indicators with standardized measurements that are easily comparable with targets, benchmarks, or other appropriate standards [11,26].

The environmental performance indicators are usually grouped into several categories. For example, Kylili et al. [22] divided the environmental category into 12 sub-categories, while Toller et al. [27] select six indicators for environmental monitoring of the Swedish building sector. Alwaer and Clements-Croome [11] identified 16 impact categories related to sustainable buildings of which 6 impact categories concern environmental indicators.

3.3. Measuring environmental building performance through indicators

Many assessment tools based on performance indicators have been developed for assessing environmental building performance. For example, Pons et al. [28] have identified 10 environmental impact assessment tools for buildings. Most of them are complex rating tools in which the assessment is made applying certification scheme specific weights to different criteria [16]. Environmental assessment tools show some common features: they are environmentally driven; based on indicators of building performances; and score based [10].

There are two basic assessment approaches for measuring environmental building performance. The first approach is based solely on life cycle assessment (LCA) while the second approach encompasses criteria-based certification tools, which in some cases also rely on an LCA approach. Amongst the most widespread certification tools are BREEAM, LEED, CASBEE, SBTool and Green Globes. They are the multi-criterion systems aiming to cover both environmental, economic and social aspects of sustainability. The tools are easy to understand and can be implemented in criteria specific steps for each criterion. A critical aspect regards the selection of criteria and weight given to each criterion. In the selection of assessment criteria, environmental aspects receive much more attention than economic and social ones. Energy efficiency is always considered the most important category amongst certification tools, followed by indoor environmental quality, waste and pollution. The development of the German DGNB certification tool puts increased focus on the quality of the building, functional aspects, and social integration is more considered than in the other certification tools [29].

Certification tools are well related to market interests and stakeholders' culture [29], but can lead to erroneous conclusions, seen from a scientific point of view [30]. These tools can make it difficult to select relevant performance indicators, and some tools are even accused of lacking vital indicators for assessing building envelope performance such as material efficiency, energy efficiency, economic efficiency and indicators based on life cycle thinking such as life cycle cost and embodied energy [24]. The US National Institute of Standards and Technology analysed the LEED system from an LCA perspective and concluded that it is not a reliable sustainability assessment system [29].

On the other hand, LCA has earlier proven to be an accepted scientific method for assessing environmental building performance [12,31,32]. LCA is an internationally standardized method of accounting for all inputs, outputs, and flows within a process, product, or system boundary to accurately quantify a comprehensive set of environmental, social, and economic performance indicators [16]. The fundamental LCA principles and the framework for life cycle assessments are outlined by ISO 14040 and the requirements and guidelines are given in ISO 14044. In addition, EN 15643 covers sustainability assessment of buildings, and EN 15978 provides the basis for the environmental performance assessment of buildings [12].

Although LCA is mainly used during building design, this assessment method can also be related to building operation. In building renovation projects, LCA is for example suitable for comparison of several products, building strategies, or building components that fulfil renovation criteria [33]. LCA can also be used for evaluating environmental building performance across property portfolios. Through the detailed result analysis, LCA can identify the weakest environmental points in buildings and highlight the most environmentally-friendly solutions. There are though several barriers for applying more dynamic LCA in practical building operation. The barriers include the perception that the LCA method is already highly data-demanding and work-intensive, and consequently costly. It is also perceived that the use of LCA building tools requires a high degree of knowledge. Other barriers to the use of LCA in general include prejudices about the complexity, arbitrary results, accuracy and problems regarding the interpretation of results [34]. Furthermore, the application of the LCA method does not guarantee a reduction of emissions or energy consumption, but it highlights weak environmental points of products (buildings) and identifies hotspots for improving environmental performance of products [35].

4. Results

4.1. EBP in a building life cycle perspective

According to EN 15978 [36], the building life cycle covers four stages: product, construction, use and end-of-life (EoL) stage. The product stage covers raw materials supply, transport and materials manufacturing. In the construction stage, building assembly takes place in which building materials are delivered to the construction site, where the construction/installation process is executed. The use stage covers building operation and maintenance period (repair, replacement, refurbishment and operational energy consumption), and in EoL stage building demolition, waste processing and disposal takes place. Benefits and impacts beyond the system boundaries are not covered by the study.

The results presented in Fig. 1 show that the research mainly focuses on EBP within the use (34/69) and product (31/69) life cycle stages. The construction stage (25/69) is less related with EBP, while End-of-Lifetime (EoL) stage is least associated with EBP (22/69). Furthermore, the study shows that almost every third article (21/69) covers all four life cycle stages indicating that EBP does not always relate to a specific life cycle stage, but covers the entire life cycle. This result supports earlier findings by Conte & Monno [10] described in theory Section 3.2.

The more sporadic focus on the construction and EoL stages is most likely attributable to the fact that the construction stage is a goal-oriented process mainly focusing on a building assembly, while the EoL stage is often disregarded due to lack of data (also on future systems such as waste processing) or is heavily simplified [37].

On the other hand, most of the research on EBP focuses on the design and use stage. The research relating to the design stage concerns extraction and manufacturing of building materials and components as well as their characteristics in relation to environmental building performance. In relation to the design stage, Basbagill et al. [38] highlight

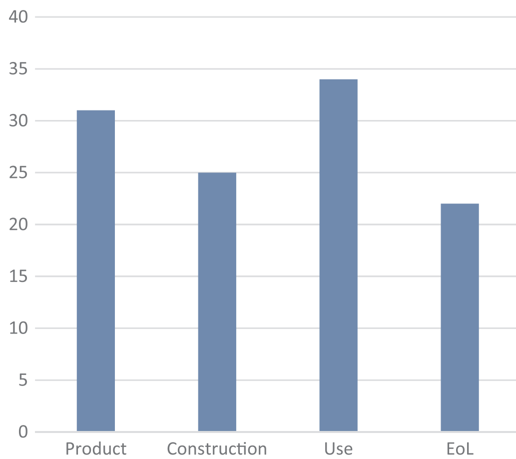

Fig. 1. The number of research articles focusing on each building life cycle stage (n = 69).

the importance of building's early stage design when determining the environmental impacts of a building. They propose a decision support method based on the integration of building information modelling (BIM), LCA and energy simulation to help designers predict the decisions that most critically determine a building's embodied impact.

The results from SLR show that the building use stage has significantly higher environmental impacts than the other life cycle stages. Nevertheless, these impacts are heavily dependent on the decisions made in the design stage, and the quality of work during the construction process. Furthermore, the actual building operation and maintenance is often different from theoretical simulations in the design stage mainly due to occupant behaviour and leads to a gap between theoretical and actual building performance.

Deeper analysis of the results for the use stage shows that the operating energy of buildings usually accounts for 80–90% of the total impacts, while embodied energy accounts for the remaining 10–20% of the total building impacts. For example, Russell-Smith et al. [16] refer to earlier studies which found that for commercial structures over 90% of the energy consumption across the life cycle and 80% of the carbon dioxide emissions stem from the use stage of the building. Russell-Smith et al. [16] also note that Scheuer et al. [39] earlier found that over 95% of the life cycle energy related impacts in a case study of a new university building stems from the use stage related consumption. Also Asdrubali et al. [40] show that the operation stage has the greatest contribution to the total impact (from 77% for a detached house, up to 85% for an office building), whereas the impact of the construction stage ranges from about 14% (office building) to 21% (detached house). In China, a study of residential buildings found that the direct operative impacts account for 68.4% of the energy consumption, 77.6% of the water consumption, 99.2% of the water pollution emission, 86.4% of the air pollution emission, and 48.4% of the solid wastes emission [41].

Another comparative study of 13 buildings found that commercial buildings have significant impacts on the environment compared to the residential buildings [42]. By comparing variables like building location (country), building type (residential/commercial), life time (year), floor area (m^2) and energy use ($MJ/m^2/50$ yr), the study shows that aggregated greenhouse gas emissions ($CO_{2eq}/m^2/50$ yr) for commercial buildings can be up to 5,600,000 t and 5.40 t for residential buildings. The study concludes that 80–85% of the total energy consumption in the building life cycle occurs during the stage of occupancy. Also Abu Bakar et al. [43] found that the range of Energy Efficiency Index (EEI) among 73 case buildings from 13 countries is 150–400 kWh/m^2/year (primary) for residential buildings and 250–550 kWh/m2/year (primary) for office buildings, indicating that the EEI values of the office buildings are slightly higher than for the residential buildings covered by the study. According to the researchers, this observation is caused by the different life cycle of office buildings and can be attributed to the fact that an office building generally requires more energy during operation due to high occupation intensity, large electrical load usage and higher energy demand to maintain comfort conditions inside the building compared with the residential building. In terms of office buildings, a study of an office building in Finland shows that the most of the covered impacts are associated with electricity use and building materials manufacturing [18]. Particularly, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing and maintenance of steel, concrete and paint, and office waste management are identified as the most impacting activities. Another study on EBP shows that the use of building materials, energy consumption and disposal of waste induces between 12 and 35 times higher environmental impacts in the use stage than the production of building materials stage. Also here the operating energy consumption is highlighted as the main source of negative environmental impact [15].

The results of our study also show tendencies against burden shifting for newer buildings in which many of the environmental impacts are transferred from the operation to embodied energy. For example, Blengini et al. [44] note that for new and low energy buildings, the relative role and the importance of life cycle stages are changing and the embodied energy can be up to 60% of the life cycle energy. Also Russell-Smith et al. [16] observe that the increased awareness of environmental problems has led to changes in the distribution between operating and embodied energy. The energy demand in the building use stage has decreased, but at the expense of using energy-intensive materials with high embodied energy and high insulation capacity. Consequently, the benefit of reducing energy consumption in the building use stage is counterbalanced by increases in the embodied energy [32]. Therefore, the lower the operating energy, the more important it is to focus on the embodied energy and assess EBP from a building life cycle perspective.

The operating energy consumption is heavily influenced by choices relating to building envelope, glazing, thermal mass of building structure, insulating materials, day-lighting and lighting control, natural ventilation and energy-recovery opportunities, and HVAC systems and operational modes such as temperature and air volume control, motors and pump types of control, indoor and outdoor air quality and environmental protection [45]. Another important factor influencing the energy demand is the ratio of the envelope surface and the building volume (m^2/m^3). The surface/volume ratio has a significant influence on the heating energy consumption per m^2 building area and therefore heavily affects impacts from the building use stage [46].

The results emphasise four main measures for improving EBP: (1) energy demand reduction, (2) installation of energy-efficient equipment and low-energy technologies, (3) installation of renewable technologies and electrical systems, and (4) changes in human factors. Nevertheless, the literature also shows that improvement measures have an environmental load in themselves and can have a negative effect on the environment [47]. For example, thicker insulation does not necessarily involve less impact because the impacts induced during the construction and disposal stages might be significant [48]. Neglecting the impacts embodied in the insulation materials may lead to solutions where energy savings might be a compensation for increased environmental burdens elsewhere [49].

Measuring EBP from a life cycle perspective is challenging due to uncertainties relating to the building life cycle. The theory section has earlier emphasised the importance of appropriate building life cycle prediction. However, from the 69 articles used in this SLR, 30 have specified a building life cycle ranging between 20 and 100 years. 33% of the articles specified a building life cycle of 50 years as a reference study period, while 20% considered 100 years as an appropriate reference study period. 10% of the articles use reference study period below 50 years, 27% of articles focus on buildings with estimated life span between 60 and 80 years, and the remaining 10% review and study buildings with different reference periods. These results are

Table 1
EBP categories and their KPIs.

Rank	EBP category	Identified articles (n = 69)	Examples on KPIs and their units of measurements
1	Energy	40	Energy consumption (kWh, MWh, GJ) Energy saving potentials (kWh, MWh, GJ or %) Energy supply (renewable/ non-renewable %)
2	Emissions	36	GHGs i.e. CO_{2e}, NOx, SO_x
3	Water	21	Water consumption (m^3) Water saving potentials (m^3 or %) Water supply – local, rain water (m^3 or %) Water pollution
4	Waste	18	Daily waste (kg, t) Building waste (kg, t) (production, treatment, disposal)
5	Land/building area	13	Property site (m^2) Total building area (m^2) Capacity (m^2/person), Occupancy rate (%)
6	Building materials	10	Aesthetics Durability (years) Thermal properties (U-value) Maintenance properties
7	Indoor Environmental Quality	9	Thermal comfort (°C) Relative Humidity (%) Daylight Air quality (ppm)
8	Reuse/recycle potential	4	Building components Building materials

consistent with earlier findings by Cabeza et al. [18] and Sharma et al. [42] showing that most research apply 50 years as a reference study period.

4.2. EBP categories and KPIs

The indicators used for environmental performance assessment of buildings are, as described in Section 3.2, usually grouped into several categories.

Based on the SLR and findings from the literature, this article proposes eight appropriate EBP categories: *building materials, energy, emissions, Indoor Environmental Quality (IEQ), land/building area use, reuse/recycling potential, waste* and *water*. The eight proposed categories are the result of identified articles within each category and its relative importance for EBP. The energy category is considered most important since it has a direct impact on EBP, but there are also categories like indoor environmental quality and land/building area that affect energy category and thus have a significant impact on EBP. As illustrated in Table 1, each of the proposed categories can include several effective KPIs. The categories in Table 1 are ranked by their importance for EBP as a result of number of identified articles for each category. Some of the categories are interrelated meaning that change in one indicator's performance can have an influence on EBP in other categories.

The results presented in Table 1 show that Energy and Emissions are the two most dominant environmental indicator categories. Energy is addressed in 40/69 articles, while 36/69 articles focus on emissions. The energy category includes KPIs relating to energy consumption, energy saving potentials, and energy supply distribution (renewable/ non-renewable energy). The emission category addresses climate change impacts through the KPIs on emissions of greenhouse-gases such as CO_{2e}, NOx, SO_X etc. Water ranks third and is considered in 21/69 articles. The water category usually includes KPIs relating to water consumption, water saving potentials, water supply, water pollution etc. The waste category is considered in 18/69 articles and uses typically KPIs to show how much daily waste and building waste is produced, treated and disposed. The land and building area use appear in 13/69 articles. The land and building area category focuses on KPIs relating to space management inside and around the buildings, and how efficiently building space is utilized. The building materials are studied 10/69 articles. The building materials category addresses building materials used for construction or renovation of buildings. KPIs for building materials usually cover building material properties such as aesthetics, durability, thermal properties, maintenance properties etc.

The least research focus is on IEQ and reuse potential: 9/69 articles consider IEQ while only 4/69 articles focus on the reuse potential. The IEQ category includes KPIs like thermal comfort, daylight, air quality etc. IEQ indicators are often described as social indicators, but since many IEQ indicators have an impact on EBP, they are in our study considered as an environmental category. Previous studies, mostly focusing on office buildings have shown that the occupants' health and wellbeing can be affected by various indoor environmental parameters, such as temperature, humidity, ventilation, natural lighting or illumination, and noise [50]. The reuse and recycling potential category considers potentials for recycling and/or reusing existing building components and materials for other purposes after their ended lifetime. This category is only considered in 4/69 articles and relates usually to studies in which the whole building life cycle is covered, including EoL stage.

Fig. 2 shows the distribution of 69 articles within 5 building research areas on EBP indicator categories. The articles on residential buildings (26/69) are mainly focusing on energy, emissions and waste, while articles on non-residential buildings (5/69) such as commercial and public buildings mostly study energy, water, land/building area use and building materials. Research articles including both residential and non-residential buildings (5/69) focus on energy, emissions, and water and waste. The research on buildings in general (20/69), which typically includes building models and simulations, focuses like research on residential buildings, mostly on energy and emissions. Additionally, it is also notable that the IEQ indicator category is most studied in this research area. Other building-related articles (12/69) covering unspecified building types, building assessment tools and sustainable development agendas show similar tendencies as the literature on four previous research topics, and focus most on energy, emissions, water and waste categories.

Deeper analysis of the results from Fig. 2 reveals that most research conducted on EBP indicators relates to energy and emissions categories. The literature study conducted by Abu Bakar et al. [43] shows that the energy consumption in buildings is largely dominated by the HVAC systems, and followed by lighting. A case study of six public buildings with retrofit actions points out that the most significant benefits related to energy savings and reduction of CO_2 emissions are mainly related to the improvement of the thermal insulation of the envelope [51]. This study also concludes that substituting lighting and glazing components provide significant energy benefits. On the other hand, both solar and wind plants involve lower energy savings and higher payback indices than predicted. Moreover, San-José Lombera & Aprea [52] emphasise that the sustainability of industrial buildings should not only be structured around energy consumption, but also include land, water, and material usage.

Results relating to IEQ reveal that if higher comfort expectations are set as a target value, this could have a direct effect on EBP, as a larger consumption of energy by the HVAC systems to maintain comfort expectations is likely to be required [53,54].

The reuse potential is not covered substantially, but there is for example research showing that the recycling of building materials in masonry buildings generates environmental benefits due to avoided impact of virgin material production [55]. Related to reuse potential, Munarim et al. [47] compare building rehabilitation with new building

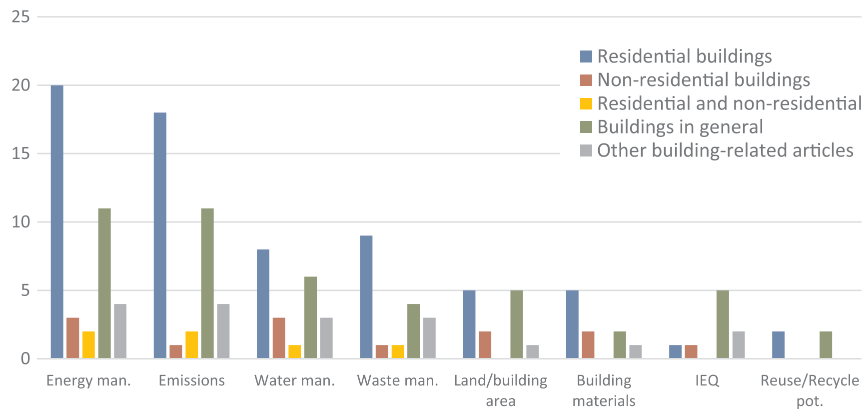

Fig. 2. Distribution of 5 research areas on 8 EBP indicator categories (n = 69).

construction and disclose that the construction of a new office building would require about 250 years more to amortise total energy impacts when compared with the rehabilitation and transformation of an old hotel building to an office building. This is due to a very small difference in estimated operation energy consumption between the new office building and the rehabilitated hotel (office) building. Munarim et al. [47] conclude that the reuse of an existing building, through its rehabilitation, conserves natural resources and energy that would be used to build a new building.

4.3. Assessment methods

The results show that the LCA method is a dominating assessment method for assessing EBP. In our study, 34/69 articles apply the LCA method for assessing EBP. The results are in line with the theory Section 3.3 claiming that LCA is a widely accepted and applied scientific method for assessing the environmental performance of buildings. The LCA case studies reviewed also confirm that the most impacting stages in a building life cycle are the use stage and the manufacturing of building materials, while construction and EoL stages are much less impacting. In the use stage, energy consumption is the dominant factor of environmental impact [56].

Although LCA is the dominant method for assessing EBP, our study notes several issues relating to the LCA approach. The LCA results depend on the approach used, data quality and the selected reference study period which in practice highly depends on maintenance activities, and may be extended by renovation, restoration or rehabilitation investments [47].

Fouquet et al. [57] recommend prospective scenarios to be used as sensitivity analysis for buildings with long service lives, because assuming current technology and consumption patterns over the next 100 years may be more uncertain. LCA studies reveal for example that energy consumption played a key role for the EBP, not only in terms of quantity consumed but also in terms of the type of energy consumed, highlighting the importance of considering energy grids as dynamic entities [49,58]. The LCA approach does not guarantee a reduction of emissions or energy consumption, but it allows for highlighting the weak points of production processes and identifying possible improvements of technology and management in the perspective of sustainable development [35].

5. Discussion

This study is based on a systematic literature review of 69 research articles. They form the basis for the analysis. By comparison with systematic literature reviews on other related topics, we argue that the number of articles is sufficient to provide a sound review of the topic.

The results of SLR show that the building use stage is the most environmentally taxing life cycle stage for most buildings. At the same time, the SLR discloses the research gap in defining the appropriate reference study period since the building lifespan in the study ranges between 20 and 100 years. There is, of course, a relationship between material longevity, durability, and the natural differences between material assemblies and components [19], but the use stage is also a variable highly depending on O&M activities. A reliable reference study period is therefore an important parameter that needs to be considered when dealing with EBP. Consequently, there is a need for a more dynamic LCA approach in practice that can illustrate the environmental impacts of different O&M scenarios, and not the conventional, static LCA approach as observed in the study. The integration of LCA approach in facilities management is though not an easy task because of difficulties in obtaining complete inventories for building components, tracking material flows and clearly defining system boundaries. The preferability of certification tools in practice is probably due to their simplicity and check list structure. LCA analyses are more rigorous and time demanding than certification tools and limited to a few specialists [29]. Moreover, existing FM software lacks not only interfacing, but also interoperability and integrations with LCA software.

Another important aspect is the relationship between embodied and operational impacts. The decisions made in the early design stage have a significant influence on the following operational impacts. On the other hand, focusing on reducing operational impacts often cause increased embodied impacts, indicating burden shifting between two life cycle stages. Reducing environmental impacts from buildings is therefore a challenge that needs to be assessed through a life cycle approach.

This SLR provides the accumulated scientific knowledge from 69 research articles on how to quantify EBP. Such knowledge is valuable for decision-makers and facilities managers in the process of implementing an environmental strategy and focusing on improving EBP. When the goal is to improve the EBP, it is essential to have a reliable data management system to ensure that the building performance is monitored and analysed properly. It is advisable to collect the data that easily can be reported as KPIs. The use of KPIs and benchmarking is fundamental to any improvement strategy and can be the right step in improving EBP. Combining KPIs with an LCA approach could provide improved system performance monitoring and deliver new insights on building performance, that later could be used for improving EBP.

6. Conclusions

The article identifies eight indicator categories commonly used for quantifying Environmental Building Performance (EBP): energy, emissions, water, waste, land/building area, building materials, indoor environmental quality, and reuse/recycling potential. Most research focuses on indicators relating to energy and emissions, while there is least research on indoor environmental quality and reuse potential, indicating research gaps between indicator categories. Keeping in mind internal dependencies between the determined categories, EBP should not only focus on energy and emissions, but also address the remaining categories identified in the article. Moreover, to be able to quantify EBP, we recommend clear definition of a building life cycle and consideration of different operation and maintenance scenarios.

The environmental impacts are generally higher for non-residential buildings than for residential buildings. Furthermore, the building use stage has significantly higher environmental impacts than the other stages, and the EBP differs between older and newer buildings in a life cycle perspective. While older buildings have the highest environmental impact during use stage, newer buildings show burden shifting tendencies towards increased embodied impacts as a consequence of lower operating impacts. Especially older office buildings induce large environmental impacts since they generally require more energy during the use stage compared to residential buildings. Still, most of the recent research focuses on residential buildings, indicating lack of research on EBP in non-residential sector.

There are two basic assessment approaches for quantifying EBP: one based solely on life cycle assessment (LCA) method, another on criteria-based certification tools like BREEAM and LEED. The LCA approach dominates in research while the certification tools are claimed more applicable in practice due to their simplicity and check list structure. We recommend the LCA approach since it is a standardised assessment method that can help decision makers choose more environmentally friendly solutions based on life cycle calculations.

Further studies are required to disclose how many of the identified indicator categories are used for quantifying EBP in practice, especially within non-residential sector. Additionally, we suggest studies on determining how LCA can become integrated in FM practice, and how FM software can support improving EBP.

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Appendix A

An overview of 69 articles used in the systematic literature review (SLR).

			Environmental category							
	Publication name	***Reference no.***	***Energy***	***Emissions***	***Water***	***Waste***	***Space use***	***Build. Materials***	***IEQ***	***Reuse pot.***
1	Pons et al. (2012)	[28]	1	1	1	1				
2	Lombera et al. (2010)	[52]	1		1		1	1		
3	Seinre et al. (2014)	[54]	1		1		1	1	1	
4	Abu Bakar et al. (2015)	[43]								
5	Malmqvist et al. (2011)	[34]								
6	Rossi et al. (2012)	[59]	1	1						
7	Thiers et al. (2012)	[60]	1	1	1	1				
8	Gangolells et al. (2011)	[61]	1	1	1	1	1			
9	Basbagill et al. (2013)	[38]		1						
10	He et al. (2013)	[41]	1	1	1	1				
11	Pajchrowski et al. (2014)	[15]	1		1	1	1			
12	Fouquet et al. (2015)	[57]		1						
13	Iyer-Raniga et al. (2012)	[62]		1	1	1				
14	Anderson et al. (2015)	[12]								
15	Soust-Verdaguer et al. (2016)	[13]								
16	Lewandowska et al. (2013)	[58]	1			1	1	1		
17	Proietti et al. (2013)	[35]	1					1		
18	Risholt et al. (2013)	[63]	1	1						
19	Nemry et al. (2010)	[46]	1	1						
20	Blengini et al. (2010)	[44]	1	1						
21	Mwasha et al. (2011)	[24]	1	1				1		
22	Moschetti et al. (2015)	[64]	1	1						
23	Islam et al. (2016)	[65]	1	1	1	1				1
24	Wang et al. (2016)	[66]								
25	Passer et al. (2016)	[32]	1	1						
26	Oyarzo et al. (2014)	[67]	1	1	1	1				
27	Debacker et al. (2013)	[68]	1							
28	Motuzienė et al. (2015)	[69]	1	1						
29	Passer et al. (2012)	[70]	1	1						
30	Blengini et al. (2010)	[37]	1	1			1	1		1
31	Franzitta et al. (2011)	[8]	1		1	1	1	1	1	
32	Cabeza et al. (2014)	[51]								
33	Häkkinen et al. 2016	[71]	1	1						
34	Lasvaux et al. 2015	[72]	1	1	1	1				
35	Asdrubali et al. (2013)	[40]								
36	Sharma et al. (2011)	[42]								
37	Mateus et al. (2011)	[26]	1	1	1	1	1	1	1	
38	Lamnatou et al. (2015)	[73]								

39	Lotteau et al. (2015)	[31]								
40	Lamnatou et al. (2015)	[74]								
41	Huang et al. (2013)	[50]							1	
42	Russell-Smith et al. (2015)	[16]	1	1	1					
43	Gou et al. (2016)	[75]								
44	Silvestre et al. (2015)	[76]								
45	Hollberg et al. (2016)	[77]								
46	Passer et al. (2015)	[78]								
47	Huedo et al. (2016)	[21]	1	1	1	1				
48	Toller et al. (2013)	[27]	1	1		1				
49	Abanda et al. (2013)	[79]	1	1		1				
50	Russell-Smith et al. (2015)	[80]	1	1	1					
51	Elle et al. (2010)	[30]								
52	Holopainen et al. (2014)	[53]							1	
53	Alwaer et al. (2010)	[11]	1	1	1	1	1	1		
54	Kim et al. (2013)	[45]							1	
55	Todorovic et al. (2012)	[81]	1						1	
56	Carreras et al. (2015)	[48]								
57	Silvestre et al. (2014)	[82]				1				1
58	Iribarren et al. (2015)	[83]	1	1						
59	Melià et al. (2014)	[56]	1	1			1			
60	Russell-Smith et al. (2015)	[84]	1	1						
61	Balaban et al. (2015)	[85]	1	1	1				1	
62	Napolano et al. (2015)	[55]		1						
63	Kucukvar (2013)	[86]	1	1	1		1			
64	Munarim et al. (2016)	[47]	1	1	1		1	1		
65	Kylili et al. (2016)	[22]	1	1	1	1	1		1	1
66	Mori et al. (2012)	[87]								
67	E. Conte et al. (2012)	[10]								
68	Lasvaux et al. (2016)	[25]								
69	Grant et al. (2012)	[19]								
Totals			**40**	**36**	**21**	**18**	**13**	**10**	**9**	**4**

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PAPER 2

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10 Questions

10 questions concerning sustainable building renovation

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ABSTRACT

In countries all over Europe the need for building renovation is receiving increased attention. One reason for this is an ageing building stock. Another reason is the need for more environmentally sustainable buildings with reductions in energy consumption and greenhouse gas emissions to limit the harmful climate impact. There is at the same time a need to upgrade many buildings to improve the quality of life – social sustainability, for instance improve indoor climate; and to increase productivity in the building process to ensure affordable housing – economic sustainability.

Low productivity and frequent conflicts in the construction sector have led to an increasing interest in new forms of collaboration between the different stakeholders involved in construction projects. Development of strategic partnerships concerning a portfolio of renovation projects are seen as a promising way to achieve more sustainable building renovation for some large building clients and for companies with a high maturity in collaborative practice.

There is a large number of tools for design decision support and systems for sustainability certification of buildings, but there are not many tools and systems dedicated to building renovation. Measuring the different dimensions of sustainability is a challenge. Regulations play a central role in opening the markets for sustainable building renovation through incentive schemes, building codes, etc. Although traditional approaches to energy renovation emphasize more efficient heating and lighting systems and better insulation, there is a tendency to address the challenge more holistically by emphasizing social targets.

1. Introduction

The need for renovation of buildings is receiving increased attention in many European countries [1]. There are many reasons for this, but essentially it comes down to a fundamental need to make building renovation more sustainable. Thus, it is important to improve the way we carry out building renovation. The authors of this paper are engaged in research and development on this topic in close collaboration with companies from the whole value chain in the Danish construction industry and we know that many researchers and companies are involved in similar activities in other countries. To support our common knowledge building, this paper creates an overview and state of the art of the existing research-based knowledge on Sustainable Building Renovation (SBR). This is done by presenting and discussing current research and by answering 10 questions.

There is a lot of research and development that focus on inventing and designing new technical solutions and developing new methods to calculate, simulate and dimension the physical and technical aspects of new and renovated buildings. On the other hand, there is much less research on how to manage and carry out the process of building renovation even though this is essential to improve the productivity, effectiveness and user satisfaction of renovation [2]. To make building renovation more sustainable, it is important to have a holistic approach on sustainability and include both the social, economic and environmental aspects. These issues have been some of the leading considerations behind the formulation of the 10 questions. The paper provides answers to the questions to create a common overview of SBR; mostly from a European perspective.

2. The 10 questions (and answers) concerning sustainable building renovation

2.1. Question 1: what are the typical issues that initiate the need for a SBR?

A European research project concerning SBR investigated the drivers for energy renovation in three European countries – Cyprus, Denmark and Sweden [1]. The drivers naturally vary for different types of buildings and organisation in each country. In Table 1 they are grouped in the main factors: Durability/building physics, Economy, Environment, Comfort and Other. It was common for all three countries

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Table 1
Identified drivers for energy renovation for three European countries [1].

	Cyprus	Denmark	Sweden
Durability/ building physics	Moisture	Deterioration	Maintenance
Economy	Cost, income	Payback time	Cost
Environment	Energy savings, Eco-friendly products	Energy savings, local energy production	Energy savings
Comfort	Indoor air quality	Indoor climate	
Other	Building aesthetics	Branding, CSR	

that energy renovation is mostly undertaken as comprehensive refurbishments, where upgrading the building in a more general sense has become necessary. Renovations only concerning energy efficiency mostly concern measures with limited payback time.

There have been many studies aiming at identifying barriers for building renovation and many proposals to categorise them have been made. Over all the barriers can simply be divided into two main categories: economic and informational barriers [2]. Lack of the financial incentives and life cycle perspectives are the most significant economic barriers, while too little political consciousness, lack of common direction amongst the main stakeholders and lack of overview, where to prioritise, are the most important informational barriers.

A recent study [3] presents an overview of barriers based on 13 literature references resulting in the following five categories of barriers; (1) Institutional and political barriers; (2) Market and economical barriers; (3) Financial barriers; (4) Technical barriers, and (5) Behavioural and social barriers.

2.2. Question 2: what is meant by SBR?

SBR is in this paper understood as renovation of existing buildings that results in upgraded buildings, which are more sustainable in terms of environmental, social and economic aspects after the renovation than before [4] – or at least in relation to two of these aspects. The meaning of sustainability is associated with the consideration of the interdependence of society, environment and economy in complex sustainability thinking based on the definitions from the United Nations with the three sustainability dimensions: social, economic, and environment [5]. For assessing sustainability of investment projects, Haavaldsen et al. [6] recommend differentiating between the three levels: operational relating to project output, tactical relating to target groups, and strategic relating to greater society.

Thuvander et al. [7] present a large list of commonly used terms to describe building changes and concludes that there is no generally used term. This paper will like Thuvander et al. [7] use the term 'renovation'. Building renovation is according to Àstmarsson et al. [8] the process of fixing or replacing existing parts of the building to improve its performance; either to its original state or better. However, renovation means renewal and is not identical with maintenance and replacing old parts with similar new parts. With renovation it is common to upgrade the building standard to be closer to the current standard rather than the standard at the time the building was originally built.

The standard of buildings produced develops over time and mostly increases, so that new buildings in general have a higher standard than old buildings. Energy requirements is a striking example. Over the last decades, the requirements to reduce energy consumption of buildings have gradually become much stricter in building regulations in most countries. Furthermore, the amount and sophistication of technical building installations or services have increased drastically. A reflection of this has been a comprehensive literature on intelligent buildings [9]. Thus building renovations provide the possibility to change building design/lay-out, functions, architectural expression etc. to match users' current and/or future needs. Combining multiple disciplines introduces complexity to building renovations, and because of that, interdisciplinary expertise is required to deal with most renovation projects [10].

The focus in this paper is on comprehensive renovation projects, which among other things involve a major improvement in energy performance. Such renovations are encouraged in European energy policies and are also called 'deep renovation', for instance in EU's Horizon 2020 programme for research and innovation [11]. A main argument for deep renovations are that they are a necessity to achieve radical improvements in energy efficiency.

However, recent research has observed a trend of housing associations moving towards applying partial or over-time renovation strategies; for instance in Sweden as well as other locations. The positive side of partial renovations is that it can provide opportunities for dealing with social issues, respect for architecture and cultural identity, and limit use of resources. They also allow for later inclusion of new technological innovations and thereby possibly achieving even higher levels of energy efficiency in the long run, while all-at-once deep renovations might lead to lock-ins to the current less efficient technologies [12]. This is an area that needs further investigation.

2.3. Question 3: who are the main stakeholders in SBR?

The main stakeholders in SBR can be divided in the demand side and the supply side. Who is involved in a specific project varies according to type of building, complexity and national traditions. The demand side consists of the owners and the users and those who represent them as facilities managers, building clients, client consultants and administrators in deciding on doing and involved in ordering building renovation. The supply side consists of the providers of design and construction services (architects, consulting engineers, contractors) as well as material and equipment providers. Besides the main stakeholders, there are often a number of secondary stakeholders involved in SBR like authorities, financiers, and neighbours. The demand side is the most interesting, when one search for motivation and barriers for initiating SBR.

An analysis from Denmark confirmed that building owners and users often have different interests, but this also varies depending on type of buildings [10]. Public schools and listed buildings are usually part of a political agenda since they get a lot of attention from the inhabitants every day. Energy renovations in social housing in Denmark are highly dependent on residential democracy. It means that the majority of the residential voters have to support the idea; otherwise it will not be realised.

Principal-Agent Problems [13] in terms of Landlord/Tenant Dilemma [8] is present in the building sector in many countries and is considered to be one of the biggest barriers for energy renovation projects. The landlord provides the tenant with housing, appliances and installations, and the tenant pays the energy bill. The landlord is therefore not interested in investing too much money in energy efficiency, while the tenant wants to lower the energy costs, and this is where the dilemma occurs. The legislation in this field is very complex and the maximum rent is regulated by law in some countries, which can be an obstacle for energy renovations because the maximum possible rent in most cases is insufficient for financing renovation investments.

2.4. Question 4: what characterizes the process of SBR compared to the process of new building?

In the construction industry it is often assumed that renovation projects merely are a special type of new construction projects. They are often organised in the same way even though mostly with a more traditional division of labour and contract forms, and less standardisation. However, there are a number of differences between the process of new building projects and the process of renovation projects. Jensen et al. [4] identify seven characteristics, which distinguish the process of building renovation from the process of new building project:

- There is an existing building and it is possible and necessary to make a pre-evaluation of the building's design, condition and performance in the planning of renovation.
- There are also usually existing users and most of them will remain users after the renovation, so it is possible and relevant to collect their experiences and views on the buildings in a pre-evaluation and their needs and preferences in the briefing process during the planning of renovation.
- It is possible to set performance target for the building after renovation related to the performance before and calculate the expected performance improvement. In new buildings, the expected performance has to be related to more general benchmarks like requirements in building codes or benchmarks for other more or less similar buildings.
- There is an existing building design and architectural expression, which has to be taking into consideration and limits the freedom for possible new design solutions. This is of particular importance, if the building is listed or categorized as worthy of preserving by authorities.
- It is usually necessary to open up some of the existing building surfaces, which very often leads to surprises compared to drawings and other documents from the original building design and in relation to condition of building materials and installations.
- It is usually much more important to involve and inform the users during the construction process than in new building projects; both because it is their building before, during and after renovation and because they will experience disturbances and perhaps even relocation during the renovation project.
- It is possible in a post-evaluation after the renovation is finished to measure and make a direct calculation of how the building performance and user satisfaction has been improved compared to the situation before, if a proper pre-evaluation was made.

In literature, there are a number of different models of renovation processes, for instance Thuvander et al. [7] and Nielsen et al. [14], and in spite of many differences they have in common a strong focus on the decision making process. A main difference between the process of SBR and new building projects is the preliminary investigation of the existing building, which is the whole basis for developing design solutions in SBR, where new building projects have the building site as a basis [7].

2.5. Question 5: what are emerging phases, forms of procurement and organisation for SBR?

The typical phases in SBR very much resembles traditional phases in construction; pre-design, design, construction and handover. There are however a number of considerations, which are unique to renovation and to building projects with a focus on sustainability. A building project with a sustainability focus must take into account a number of factors, and not only consider them in the design, but also be ready to do quality control and commissioning to ensure that the sustainability targets set for the project are realized. Sustainability is a broad topic and the project organization must articulate, prioritize and execute sustainability targets that can be environmental, social or economic in nature. The project can use internally defined sustainability goals or utilize building rating systems, see further in section 2.7.

The procurement process for building projects with a sustainability focus can take several forms as with other building projects. The traditional form with "Design-Bid-Build" approach separates the pre-design and design from the construction and handover. A "Fixed Price" strategy can be used by the building client to transfer the risk to the contractor, or if the building client wants to assume all the risk, a "Cost Plus" contract can be made [15]. Apart from the traditional forms of contracting, which usually is provided by local governments or officially sanctioned bodies, bespoke construction contracts can also be used. This has been reported in the UK, where 51% of the respondents to the NBS National Construction Contracts and Law Survey 2015 reported having used bespoke contracting [15]. Bespoke contracts are tailored to the task, but they results in relatively expensive projects and are not suitable in a wide range of circumstances. They are made by legal teams specialized in construction contract law in the specific country, where they are applicable.

This traditional procurement process can be broken up into a number of discrete operations. While this way of procuring comes with a number of advantages, the drawbacks are high transaction costs and low levels of coordination. A number of initiatives have been instigated to overcome these shortcomings and can be grouped under the umbrella term Relational Contracting [16]. In relational contracting emphasis is put on creating trust and collaborative teams and has led to schemes such as: Integrated Project Delivery, Partnering and Strategic partnerships/alliances. The creation of trust in relational contracts entails using a wide range of strategic, tactical and operational tools, for instance alignment of goals and values, bi- or multi-lateral governance, transparency in budget allocation and expenses, holistic risk assessment and allocation, systematic workshops, and education of staff in handling partnerships [4,16,17].

2.6. Question 6: what examples exist of new forms of partnerships for SBR?

Conditions vary greatly from country to country, when it comes to the sophistication and variety of partnerships being used in the construction industry. For the last two decades sophisticated strategic partnerships have been used in the UK; most noticeably by central and local government building clients. These practices of strategic partnerships or alliances have spread to several other countries and have yielded positive results with regards to a great number of parameters, including budget certainty, completion time and client satisfaction [17].

When establishing an organisation to execute a SBR, it should be arranged in such a way that it can handle the many barriers facing such a project [18]. One of the main barriers to both sustainable new buildings and renovations concerns the targets or mitigating strategies. There is a general lack of knowledge in relation to this, which means that the building brief usually does not contain such targets and mitigations or that they are not brought into the building operation phase [19].

When evaluating the most cited research on barriers to sustainable building and challenges regarding renovation projects, it seems that strategic collaboration employing framework contracts can be beneficial [4]. A strategic collaboration, also called a strategic partnership or alliance, consists of a building client, who enters into a long-term contract with a consortium consisting of architects, consulting engineers and contractors. In such a collaboration, it is possible to have early involvement of experts and contractors in the pre-design and design phase. This enables the state of the non-renovated building to be assessed better and ensures that sustainability criteria and technologies are implemented correctly. When the team in a strategic collaboration works well, it will over time be able to implement improved solutions, which benefit from better communication and cross-disciplinary understanding. In a framework contract with several projects, it is possible to implement novel solutions and learn how new technologies, processes and methods can be implemented across projects to further improve sustainability parameters.

The core strength of the strategic collaboration is the companies' priority of resources on a strategic level, the interconnection of systems and communication and the use of teams, which can collaborate and learn across multiple projects. However, such implementation is not

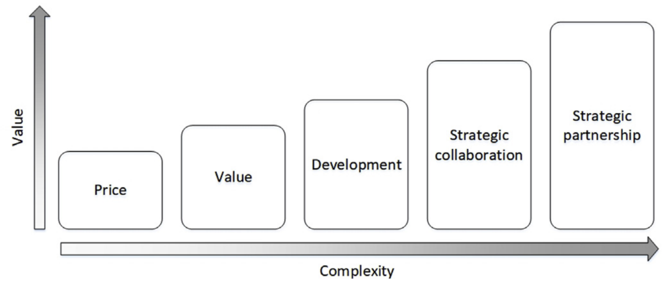

Fig. 1. Strategic collaboration in construction maturity model (adapted from Ref. [22]).

without difficulty and requires both a mature building client and mature consortium [20]. Implementation and development of a mature client side has been found to be possible both through a national top down approach with a mandate to government building clients about using strategic collaboration and through a bottom up approach with individual building client [4]. The top down approach has been effective in the UK at pushing the concept of strategic collaboration, but it has by no means resulted in universal adoption [15,21]. The bottom up approach found in Sweden and Denmark has yielded positive results for the involved building clients and consortia, but it is not broadly adopted in the two countries [17].

Several models have been proposed to support and mature the consortium and each company in the consortium to enable them to participate in strategic collaborations. One such model can be found in Johansen et al. [22], where Key Attributes (KA) are used to highlight both the positive aspects of strategic collaborations - values, and the difficult aspects – complexities, see Fig. 1. The model identifies a stair with five steps that may categorise a company's maturity level in this respect. This also offers ideas or guidelines about the next step.

2.7. Question 7: what tools exist for target setting and evaluation of SBR?

There are many decision support tools and several systems for sustainability measurements and certifications of buildings. The decision support tools are tools and methods that can help decision makers such as professional building owners to make more informed decisions, when dealing with SBR. The decision support tools are mainly used in the early stage of renovation projects (pre-design and design phase) and are primarily focusing on performance estimation, criteria weighting and design alternatives generation [14]. Some of the most widely spread decision support tools are EPIQR (residential buildings), TOBUS (office buildings), XENIOS (hotels) and INVESTIMMO (residential buildings).

There are several international standards that address sustainability in buildings. These standards can be used for setting the goals for planning and building construction. CEN's Technical Committee 350 (CEN/TC 350) covers a suite of European standards covering the assessment of sustainability for construction products, buildings and the wider built environment. These standards are relevant for the assessment of integrated performance of buildings over their life cycle. EN 15643 [23] covers sustainability assessment of buildings (part 2 - environmental, part 3 - social, and part 4 - economic performance). While EN 15978 [24] provides calculations for the environmental assessment of buildings [25].

Previous studies have shown that the earlier sustainability assessment is conducted, the greater is the potential to effectively influence building performance. However, evaluation of building performance is typically not performed until the design development stage or later due to several barriers: data availability, lack of building designer expertise, and lack of quantified environmental targets and inability to measure performance against these targets [26]. Risholt et al. [27] suggest that sustainability assessment of building renovations should be based on a lifecycle analysis applying three types of indicators; performance indicators, economic indicators and social and usability indicators. This is in line with Mjørnell et al. [28,29], who present a tool to evaluate different renovation alternatives based on environmental, economic and social life cycle assessments.

A critical review of 16 different building environmental assessment tools disclosed that half of the tools can be used for existing buildings, but only 5 of those are suitable for assessment of building renovations [30]. A more recent study found 8 building assessment methods of relevance for assessment of building renovation [7]. Criteria-based certification systems like BREEAM, LEED and DBNG are complex rating tools in which the assessment is made applying certification scheme specific weights to different criteria [31]. Their purpose and evaluation methods are different, and they vary in scope, structure, format, complexity and in the sustainable energy performance indicators used. They also lack some vital indicators that can be used to assess the sustainable performance of building envelope such as material efficiency, energy efficiency, economic efficiency [32]. However, the certification systems also show some common features: they are mainly environmentally driven, based on indicators of building performance, and score based [33].

Besides international standards and certification systems, there is a broad variety of decision support tools relating to sustainable renovations. For example, Nielsen et al. [14] identified 43 decision support tools applicable in SBRs. However, only 9 of identified tools include the aspect of goal setting, while only 5 tools provide explicit guidelines for evaluation of design alternatives. Decision support tools like Renobuild [34] and RENO-EVALUE [10] are some of the tools that can be used for goal setting. Post Occupancy Evaluation (POE) tools like for instance Building Use Studies [35] can be used for evaluating final results of renovation projects. Several overviews and comparisons of various POE tools have been published [36–38].

2.8. Question 8: how can sustainability targets be measured for SBR?

The targets for SBR are measured through a combination of different parameters originating from environmental, social and economic dimensions of sustainability. Although measuring the different dimensions of sustainability is a challenge, several tools and databases with various degrees of maturity exist.

Environmental targets for SBR aim at reducing resource consumption and negative environmental impacts. The targets are measured through parameters such as consumptions of energy, water and waste, emissions of CO_2 and other pollutants, as well as environmental life cycle assessments of the whole building before and after renovations. Studies show that 80–90% of negative environmental impacts occur during building use stage, while 10–20% of impacts are related to building construction and end-of-life stage [39,40]. Furthermore, studies show that a majority of negative environmental impacts from building use are caused by building operating energy [41,42]. Thus, reducing operating energy and increasing the share of renewable energy consumption are typically main environmental targets within SBRs.

Life cycle assessment (LCA) is an internationally acknowledged method for assessing environmental performance of products. LCA principles are outlined by international standard ISO 14040 [43] and the requirements and guidelines are given in ISO 14044 [44]. This assessment method requires large data sets and is time demanding, but very useful in highlighting the most environmentally friendly products. In SBRs, LCA software tools like GaBi and openLCA can evaluate environmental impacts of different renovation solutions or single building components. Pons et al. [45] have identified 10 environmental impact assessment tools for buildings.

Social targets focus on subjective evaluations in terms of user satisfaction, and objective evaluations in terms of indoor climate and health parameters before and after renovation. Such targets are sometimes called non-energy benefits (NEBs) [2]. For example, improving indoor climate quality may not directly have feasible financial effects or reduce negative environmental impacts, but the research shows that improving indoor climate quality in office buildings reduces sickness amongst employees and provides increased productivity [46]. Social targets are described in EN 15643-3 [23] and can be measured through indicators for the following social performance categories: accessibility, adaptability, health and comfort, loadings on the neighbourhood, maintenance, safety/security, sourcing of materials and services, and stakeholder involvement. There are, as mentioned in section 2.7, attempts to develop social life cycle assessment, but there is a lack of standardised methods for such assessments [28].

Economic targets consider financial parameters like operational cost, rental cost, asset value and life cycle cost before and after renovation. Payback time is often the most important parameter when considering SBRs [2]. It is usually only calculated by considering the initial investment and the direct annual operational cost saving without taking indirect costs and the time value of money into account. Therefore, it is a simplified calculation, while calculations based on life cycle cost (LCC) of net present value can give more precise results. LCC methodology refers to standards ISO 15686-5 [47] and EN 16627 [48].

Sustainability targets are often assessed through criteria-based certification tools, which in some cases also rely on LCA and LCC credits. For example, DGNB includes LCA and LCC credits, while BREEAM incorporates LCC credits. If the property owner or building user asks for it, a specific certification can be achieved after building renovation, depending on building performance within environmental, economic and social parameters.

2.9. Question 9: what institutional factors enables and inhibits SBR?

The realization of SBR are enabled and inhibited by a wide range of institutional factors. The inhibiting factors include handling cultural heritage buildings combining original practices and solutions and cost-effective and energy-efficient mainstream solutions [49]. Furthermore, several issues relate to financing [50] like high capital cost, unclear return on investments, fair sharing of benefits and costs between tenants and landlords, and regulated limits for increasing rents and thereby minimizing the risk of renoviction, where landlords use refurbishment projects to boot out long-time tenants that cannot afford the substantial increase rent.

On the enabling side, regulation and policymaking play a central role in opening the markets for SBR through incentive schemes, building codes, certification schemes, etc. These initiatives not only relate to national states but are also developed and implemented at subnational and supranational level. The drivers at the subnational levels are primarily cities or regions. An example is the emissions trading Cap-and-Trade policy [51] successfully implemented by Tokyo Metropolitan Government using market mechanism to allow the most cost-effective renovations to take place among the very large buildings in the city [52].

At the national level, the focus is on traditional initiatives such as building codes and regulation of energy prices. However, also new concepts emerge here like the Dutch EnergieSprong, which began as a government funded innovation program for the social housing sector [53], but now has spread to countries like Germany, France, Italy, UK, US and Canada [54]. This approach is based on highly-industrialized retrofit processes and the conversion of the energy bill into a financial source to support refurbishment of the building stock with long-term performance guarantees [55].

The national governments might even further be influenced by “supra-national” requirements most notably exemplified by shared directives in the European Union (EU). Key EU legislation like the Energy Performance of Buildings Directive (EPBD) [56], together with the Energy Efficiency Directive (EED) [57], the Renewable Energy Directive (RED) [58], the Ecodesign Directive [59] and Energy Labelling sets a framework for long-term improvements in the energy performance of Europe's building stock.

Determining the most effective set of policies to significantly improve the existing building stock is a key challenge for energy policy makers around the world. Here it is not just important to consider the building in itself, but to see the building in the wider energy system. The increasing share of renewable energy in the grid creates a need not just for more efficient systems, but also more flexible consumption practices and technologies [60,61]. A recent review by IPEEC Building Energy Efficiency Task Group categorize four generic policy instruments [62]:

- Performance based renovation targets and requirements
- Building energy codes/standards applied to existing buildings
- Mandatory energy performance disclosure, sometimes linked to upgrade requirements
- Voluntary standards that become mandatory with financing from certain sources

In practice, the actual policies are a configuration of the above-mentioned policy instruments targeting the specific sub-, supra- and nation context taking into consideration areas like (historical) building types, key industry capabilities, and fiscal systems. Despite the different contextual factors, the policies that appear to deliver the most significant activity in building energy renovation are the following [62]:

- Comprehensive improvement targets, supported by underlying policies and initiatives including regulations, financing, and information campaigns aimed toward various stakeholders.
- Disclosure of energy performance, with mandates tied to improving the performance of the poor performers.
- Linking financing and other supportive policies to deeper savings, through tiered incentives where very deep renovations are rewarded.
- Some role for a “renovation facilitator” to navigate different policies and stakeholder groups needed for implementation of deep renovations.

2.10. Question 10: what are typical and emerging concepts and technologies for realising SBR?

With regards to technology to be used for SBR, the amount and sophistication of building materials, technical installations or services has escalated over the past decade. Table 2 identifies and evaluates some the most common technologies for SBR, inspired by the hierarchical process towards zero carbon refurbishment by Ma et al. [63] supplemented with recent sources like Pacheco-Torgal et al. [64]. Here we only look at the technologies for the building omitting the wider energy supply like gas and district heating.

The technological development of new building technologies increases the solution space for SBR and sets requirements for the processes connecting the specific challenges with technological solutions. Fuelled by the increasing digitalization, existing and new process technologies promise to help decision makers navigate the complexity and epistemic uncertainty of the specific projects. The reduction of epistemic uncertainty through collection of data for existing buildings has traditionally been supported by “destructive practices”. Here parts of the building are destroyed to uncover important information about the structural principles, thermal bridges and current state of building materials, including moisture and mould. However, new technologies have made the collection of data about buildings easier and non-destructive. This includes thermal cameras for tracking thermal bridges and insulation patterns, and moisture measurements or indications based on electromagnetic induction methods [65].

Furthermore, new 3D scanning techniques create 3D models of existing structures [66]. While these currently represent advanced technologies, the current improvement of the sensors and extra cameras in

Table 2
Building technologies for SBR categorized by their main function [64].

Main function	Technology	Benefits	Challenges
Heating and cooling demand reduction	Thermal insulation materials	- Simple and practical components - Well proven technology - Saves energy - Improved indoor climate	- Health and safety challenges during installation
	Paned windows and glazing	- Better indoor climate using natural lighting - Letting the outside in - A source for heating	- Optimal solution very dependent on geographical location and orientation - Must potentially be supplemented with solar shades
	Air tightness	- Minimizing heat loss - Inexpensive and effective - Better comfort by reduced draught	- Potentially source for humidity and subsequently mould - Difficult to achieve 100% airtightness
	Reflective materials	- Simple and effective - Reduce the summer heat-island phenomenon. - Make buildings and cities comfortable places to live.	- Reflections influence stakeholders around the building
Energy efficient equipment and low energy technologies	Thermal storage capacity	- Principle well known - Saves energy - Improved comfort - Decreasing temperature fluctuations	- Phase Change Materials represent an immature technology
	Smart heating systems	- Improved comfort - Saves energy - Better energy utilization - Automatic temperature adjustments - Relatively low cost of implementation	- Potentially complex integrated systems - Sometimes incompatible with user behaviour
	Lighting	- Low cost - Long lifecycles - Moving towards SMART solutions	- Fast development compared to other technologies - More advanced systems
	Heat recovery	- Considered more efficient than natural ventilation - Can ensure better air quality and indoor climate	- Requires maintenance
Renewable energy supply	Solar Air Collectors (SACs)	- Simple and effective - Heat producing - Ventilation by fresh air - Ideal for small buildings	- Limited adoption on larger buildings
	Photo Voltaic (PV)	- Multifunctional - Electricity producing - Part of the envelope - Rapidly decreasing costs - High durability	- Still limited adoption in SBR - Design challenges with integration. - Depending on location and orientation
	Solar thermal	- Primarily suitable for preparing hot water and providing space heating. - Simple well-proven technology	–
	Heat pumps	- Air source heat pumps are considered as better options for building refurbishment due to its ease of installation and less space requirement comparing with ground source heat pumps.	- Requires maintenance - Potentially large systems (ground)

mobile phones suggest that 3D scans in the future might be a feature in our hands [67].

3. Conclusions

In the first stage of developing this paper we formulated 10 questions concerning the proposed topic of Sustainable Building Renovation (SBR) and provided an answer in one sentence to each question. We conclude the paper by giving our reconsidered one sentence answers.

1. The typical issues that initiate the need for SBR can be grouped in the main factors: durability/building physics, economy, environment and comfort.
2. SBR is renovation of existing buildings that results in upgraded buildings, which are more sustainable in terms of environmental, social and economic aspects after the renovation than before – or at least in relation to two of these aspects.
3. The main stakeholders in SBR can be divided in the demand side, consisting of the owners and the users and those who represent them, and the supply side, consisting of the providers of design and construction services as well as material and equipment providers.
4. The main characteristic that distinguish building renovation from a new building project is that there is an existing building and often existing users and one needs to make a pre-evaluation of the building and the experience of using it, which can be used as a starting point and a baseline for a post-evaluation.
5. The typical phases, forms of procurement and organisation for SBR resembles the traditional situation for new building projects, resulting in high transaction costs, but there are a number of initiatives to overcome these shortcomings, which can be grouped under the umbrella term Relational Contracting with an emphasis on creating trust and collaborative teams.
6. For the last two decades sophisticated strategic partnerships have been used in the UK - often based on the use of framework contracts covering a portfolio of renovation and/or new building projects, and these new forms of collaboration have spread to several other countries.
7. There are not as many tools and systems for decision support dedicated specifically to building renovation and there is a lack of simple tools for target setting and evaluation of SBR, but several international standards address sustainability in buildings.
8. The targets for SBR are measured through a combination of different parameters originating from the dimensions of sustainability – both separately, for instance in environmental, social and economic life cycle assessments, and jointly in comprehensive building certification systems.
9. Regulation and policymaking play a central role in opening the markets for SBR through incentive schemes, building codes, certification schemes, etc., but there are also a number of inhibiting factors including handling of cultural heritage buildings.

10. The amount and sophistication of building materials, technical installations and services have escalated over the past decade and some of the most promising areas of development are related to heating and cooling demand reduction, energy efficient equipment and low energy technologies, renewable energy supply as well as digital tools and diagnostic methodologies. However, much of the development is still in the laboratory.

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PAPER 3

(P3)

Technical University of Denmark

The implementation impacts of IT systems on energy management in real estate organisations

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ABSTRACT

Purpose: Real estate organisations change over time, but they must always have a proper overview of their building portfolio and performance to ensure efficient facilities management. IT systems and access to valid data can provide the overview and bring other benefits to real estate organisations. The paper studies which impacts the implementation of IT systems Integrated Workplace Management System (IWMS) and Energy Management System (EMS) has on energy management in real estate organisations and for their customers/tenants.

Method: The theoretical framing includes aspects of change management and organisational theory. The research is based on a case study of IWMS and EMS implementation. The case is The Danish Building and Property Agency (BYGST) that manages a large property portfolio (over 4.000.000 m^2) and currently implements IWMS and EMS as part of an organisational change process. The empirical data is collected through field observations and document studies. Document studies include project initiation documents, system design documents on energy management and observation notes. The study is a snapshot of the implementation and covers period March-December 2017.

Key findings: The study indicates that the implementation of IWMS and EMS can provide more consistent data on the building portfolio and ensure better overview of actual building performance. The successful deployment of IWMS and EMS is though conditioned by several prerequisites such as availability of internal resources and their competences, and clear definitions of which business processes the new IT systems should support. The results indicate that energy management can be improved when valid core building data and consumption data is provided, combined, and properly presented to different stakeholders such as energy specialists, facilities managers and tenants. Furthermore, the systems can be used for reporting and benchmarking of energy consumption across the building portfolio.

Impacts of the study: The paper shows how real estate organisations, including FM departments, can use IT systems IWMS and EMS for energy management. The study shows that new, exhaustive insights on energy consumption and usage patterns increase focus on actual energy performance across the building portfolio and highlight possibilities for further energy optimisation and energy savings in practice.

Keywords:

energy management, IWMS, EMS, dynamic data, building performance

1 INTRODUCTION

Buildings in the EU are responsible for 40% of energy consumption and 36% of CO_2 emissions (European Commission, 2018). The average specific energy consumption in the non-residential sector is 280 kWh/m^2 which is at least 40% larger than in the residential sector. While hospitals, hotels and restaurants represent the highest energy intensive type in specific terms, offices, wholesale and retail trade buildings, on the other hand, represent more than 50% of energy use. Education and sports facilities account for 18% of the energy use while other buildings account for 6% (BPIE, 2011).

IT systems and valid consumption data can improve energy management and bring other benefits to real estate organisations. However, successful IT implementation is an extremely complex process which normally concerns the whole organisation. It is a process beginning as a concept and ending with the implementation, and must therefore be managed as an organisational change project. The implementing conditions become more favourable when the benefits of the IT system are demonstrated during the implementing process (Madritsch and May, 2009).

In facilities management, IT software systems can be divided in Data Containers (e.g. FTP servers, databases and BIM) and Workflow Systems (e.g. CMMS and CAFM) (Ebbesen and Bonke, 2014). This paper studies the workflow system Integrated Workplace Management System (IWMS) and the supporting Energy Management System (EMS).

The research and advisory company Gartner invented the term “Integrated Workplace Management System” in 2004 and defined IWMS as an enterprise suite that includes five components: capital project management, real estate/property portfolio management and lease administration, space and facilities management, maintenance management, and sustainability/facility optimisation and compliance (Schafer, 2014). In other words, IWMS supports organisations in managing and optimising real estate portfolio and business processes including lease administration, project management, space management, maintenance management and environmental sustainability. In the European context, IWMS comes very close to the understanding of Computer Aided Facility Management software (CAFM) (Madritsch and May, 2009).

The purpose of this paper is to demonstrate how real estate organisations (including FM departments) managing non-residential buildings can improve energy management through the implementation of IWMS and EMS. The goal is achieved by studying the research question: What are the implementation impacts of IWMS and EMS on energy management in real estate organisations? The research question is answered through findings from a case study of a public real estate organisation.

The paper begins with theoretical framework in section 2 and describes the research method in section 3. It then presents the case study in section 4. Findings and discussion are in section 5 and the conclusions are in section 6.

2 THEORETICAL FRAMEWORK

Technology is usually the element indented to stabilise a rather fragile change. Three dimensions are important when technology is used for change: coverage, functionality and dynamics (Kamp et al., 2005a). Coverage explains technological coverage of a company as the supplier imagines it. Functionality defines what the technology can and is usually described in modules or blocks. Dynamics highlights that technology is not static, but develops over time. Many dynamics are at stake after planned change. Internal and external development impacts organisational change both intentionally and unintentionally. There are for example intended internal changes in the organisation, and unintended external changes like suppliers offering new system versions, modules or systems that by implementation change parts of the organisation.

There are, according to Mintzberg (1980), five basic organisational configurations (Simple Structure, Machine Bureaucracy, Professional Bureaucracy, Divisionalized Form, and Adhocracy) and five basic mechanisms of coordination (mutual adjustment, direct supervision, and standardisation of work processes, outputs and skills) in an organisation. Implementing an IT system like IWMS to real estate organisations could e.g. contribute to standardisation and change the organisational configuration.

The strategic improvements in business value are called benefits and are usually achieved through programme and project management. The creation of business value depends therefore strongly on programmes and projects delivering the expected benefits, as illustrated in Figure 1 (Serra and Kunc, 2015).

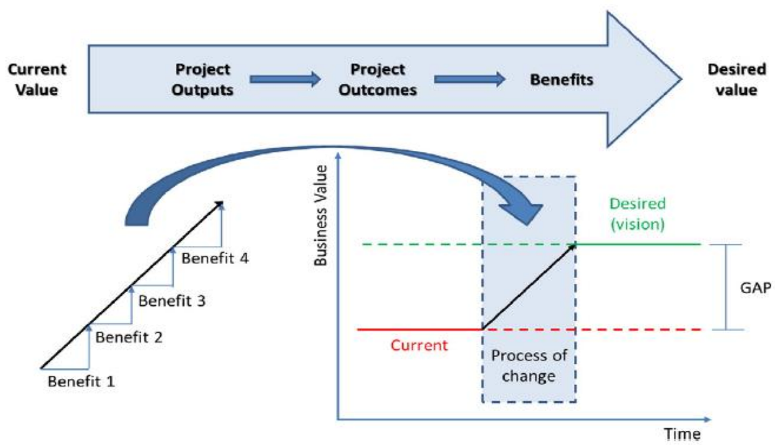

Figure 1: Moving from current to desired business value requires changes. (Serra and Kunc, 2015)

Business Process Reengineering (BPR) considers IT as a tool for supporting and enabling changes in business processes. Reengineering restructures business processes across entire organisation through radical thinking, while IT is only a lever for such process changes (Hviid and Sant, 1994). IT systems must inevitably support activities relating to cross-disciplinary business processes and solve issues with long lead times, high management, administration and overhead costs, and break down barriers between subject areas, functions and between organisation and its surroundings in general. The focus is on customer needs and value creating processes (Kamp et al., 2005b; Jensen, 2008).

IT implementations are cross-disciplinary and include different stakeholders (e.g. top management, consultants, system users). Determining the relationship between different stakeholders and new IT systems, as well as the impacts of implementing process on the organisation, is therefore important. The implementing process can include different impacts on: improvements and changes of the technology (*product innovation*), the work processes which the technology is meant to support (*process innovation*), and cause or require improvements and changes in the organisation (*organisational innovation*) (Ebbesen and Bonke, 2014).

Implementing IT systems changes the way organisations operate and perform. Change management includes two basic concepts for managing changes in the organisation: quasistationary equilibrium and permanency (Ebbesen and Bonke, 2014). Quasistationary equilibrium reflects the level of behaviour between forces pushing for and resisting change. The relationship can be changed by either adding forces, or removing the resisting forces (Hayes, 2010). Removing the resisting forces, rather than adding forces, is more likely to result in a more permanent change. Permanency defines that successful change requires three steps: unfreezing, movement and refreezing. Unfreezing means destabilizing the balance of driving and restraining forces. Movement modifies the driving and restraining forces towards a new state. Refreezing reinforces the new state and avoids a relapse. When studying an implementation process, it is important to highlight in which step the study takes place.

IT implementation changes the technological component and thereby triggers changes in the other components of the organisation (Ebbesen and Bonke, 2014). The expansion of knowledge requires extensive input from the field. Communication and user involvement in the organisation in the early stage is crucial, especially because IT implementation typically runs over several years (Foley, 2012).

Identifying which changes will occur and ensuring realisation of desired vision can be complicated. Successes in IT projects depends on categories such as system quality, information quality, information use, user satisfaction, individual impact and organisational impact (Ebbesen and Bonke, 2014). IT systems that are not in line with company traditions and root processes have higher failure rate (Kamp et al., 2005c). Some IT systems are more complex than expected and bring unexpected and changed routines to the organisation. Studying different categories can reveal whether the implementation leads to failure or success.

3 METHOD

The research is based on a qualitative case study of IWMS and EMS implementation (Yin, 2014). The Danish Building and Property Agency (BYGST) currently implements IWMS and EMS as part of an organisational change process and is therefore selected as a case.

The implementing process involves three companies: Trimble, KMD, and Implement Consulting Group (ICG). Trimble is a global software developer and provides IWMS solutions. KMD is a large Danish IT company responsible for delivering Trimble's IWMS and own EMS solutions to BYGST. The first author is industrial PhD candidate affiliated to KMD and has as such achieved access to research data presented in the paper. ICG is an external consulting company hired by BYGST and is responsible for the implementing process.

Field observations and document studies are used for collecting the data. The study is based on observations from 6 implementation meetings, 4 workshops, and 7 observation days on-site. Implementation meetings cover internal KMD meetings, and meetings between KMD/Trimble business specialists and BYGST's energy specialists on energy management design solution. Workshops cover team sessions including representatives from all four organisations involved in the implementation. On-site observations are personal observations from BYGST's headquarter.

Furthermore, the study is supported by document studies of project initiation documents, system design documents on energy management, and notes from meetings, observations and workshops.

The system implementation is still ongoing, and the complete solution will go live December 2018. The EMS is partly implemented and has collected consumption data from office buildings since

May 2017. The study presented in this paper is a snapshot of the implementation and covers the period March-December 2017. The results are therefore preliminary, and a follow-up study is planned.

4 CASE STUDY AND RESULTS

4.1 About BYGST

BYGST is the Danish state's property enterprise and developer whose main task is to provide work spaces and office and research environments on market terms for its customers, including universities, central administration, police and the courts. BYGST was established in October 2011 as part of Danish governmental formation. Several governmental agencies (part of the Agency for Palaces and Properties, University and Building Agency, Business and Construction Agency) have been consolidated into BYGST, and the agency is still undergoing organisational changes. BYGST solves its task by owning and renting out buildings of the state through new construction and modernisation, and by redistribution of private leases to the state institutions. The agency has about 300 employees that manage 1.800 leases covering more than 4 million m^2 of building area. About 1,2 million m^2 are private leases and public-private-partnerships, 2 million m^2 are used by the universities, and approximately 800.000 m^2 are office buildings owned by BYGST (Bygningsstyrelsen, 2017a).

BYGST’s current IT system landscape is diverse due to former reorganisations, different employee needs, working cultures and local IT-solutions emerged over many years prior to the consolidation. The IT system landscape is a product of long-term accumulation of silo-based systems that support individual needs of different departments at BYGST. The agency has characteristics of Divisionalized Form and faces challenges in maintaining and developing many diverse IT systems. Furthermore, several IT systems contain same type of data that is updated individually in each system, leading to missing coordination and poor data quality. BYGST therefore needs a more consolidated IT system landscape that can reduce the amount of IT systems and secure consistent, valid data across the entire organisation. For solving the problem, BYGST visited several real estate organisations using IWMS outside Denmark (The Dutch Building and Property Agency and 4 companies/municipalities in UK). Based on the experiences and recommendations from a market survey, BYGST decided to introduce IWMS (Bygningsstyrelsen, 2015). The internal need analysis and the market survey was initiated in 2012. The tendering and contract sign-off took place in 2016. The implementing process (design-build-test) was initiated in early 2017 and runs till the end of 2018.

BYGST has a vision of being the preferred property manager for customers and the state. The strategic goal is to build up a strong, data-driven knowledge organisation concerning work spaces and efficient building processes, construction and facilities management. A stronger, data-driven knowledge organisation is expected to create the basis for advising and decision-making that will result in cost effective solutions for the agency and their customers (Bygningsstyrelsen, 2012). By introducing IWMS and EMS to Business Process Reengineering, BYGST wants to combine data, knowledge and professional experience to change the organisational configuration and deliver improved customer service.

The external implementation consultants ICG and BYGST have developed benefit realisation diagrams for defining changes and goals of IWMS and EMS implementation. Several benefits from IT implementation must be realised to achieve strategic vision: higher customer satisfaction with BYGST's service, more time for new tasks, decrease in IT-costs, increased process coherence, more valid data, and better IT security.

4.2 Energy management – benefit realisation diagram

BYGST does not consider the IWMS/EMS implementation as a definite IT project, but as an organisational change process consisting of several module-specific implementation projects. Each module has its own benefit realisation diagram and implementation track.

Regarding energy management, BYGST has a special role in pointing out possibilities for reducing the energy consumption in buildings and instructing tenants on energy savings (Bygningsstyrelsen, 2012). By implementing new IT systems, BYGST also puts focus on energy management of the property portfolio. The benefit realisation diagram in Table 1 shows which changes and goals IWMS and EMS must realise to deliver energy management benefits for the agency.

Table 1: Benefit realisation diagram for energy management at BYGST. (ICG 2017)

Deliveries	Skills	Behaviour	Effect	Goal
User (BYGST employees) training *IWMS (Energy module)* *EMS* *Web module for Tenants* *Importing building data in EMS* *Two-way integration between IWMS and EMS*	*Energy dept. can use EMS and IWMS* *Energy dept. can create energy reports in IWMS for different organisational levels* *Energy dept. can set necessary alarms for i.a. higher energy consumption* *Exchanging data between IWMS and EMS*	*Consumption is calculated through distribution keys* *Appointing responsible BYGST employees for monitoring and optimisation proposals of energy consumption* *Monthly e-mails to customers regarding their individual energy consumption* *Quality control of energy data once a week* *E-mail notifications to BYGST's energy responsible in case of higher energy consumption*	*Energy savings for customers thorugh increased focus on consumption* *Time savings on data retrival* *Time savings for reporting on energy data* *Increased customer satisfaction with energy managmeent* *Increased customer enquiries regarding energy saving measures* *Less customer enquiries regarding data validity*	*Contribute in creating a solid foundation for BYGST's eligibility* *Better customer service* *Savings on energy consumption* *Valid energy data* *Increased employee satisfaction*

The deliveries encompass the implementation of IWMS and EMS with connected webservice for tenants. The data must be imported in the systems, and two-way interface between IWMS and EMS must be developed. BYGST employees must also receive user-training in the systems.

Changes are reflected through developing new skills and behaviour in the organisation. The Energy department must be able to use and exchange data between IWMS and EMS, and to create reports for different organisational levels. The Energy department must also develop skills in configuring notifications for e.g. higher energy consumption. Customers will receive monthly notifications regarding their energy consumption. BYGST's energy responsible person will receive notification in case of higher energy consumption. Once a week, quality control of energy data is performed. The aim is to provide energy savings for tenants (external development) and time savings on data retrieval and reporting (internal development). The deployment of IWMS and EMS must increase tenant focus on energy management and energy savings, and reduce enquiries regarding data validity.

4.3 Design solution

Figure 2 shows the design solution for energy management at BYGST. The model is designed to support different stakeholder needs on consumption data in and outside of BYGST. The implementation includes a module-based IWMS "Manhattan Software" (called "KMD Atrium" in Denmark) covering Core, Lease, Customer Relationship Management, Project and Energy modules. Each module has its own implementation track in a project. Besides IWMS Energy module, the EMS "EnergyKey" and the connected webservice "Webtools" are also included in the energy management track. EnergyKey manages energy data collection, meter readings, data analysis, consumption visualisation and reporting. Webtools is an add-on module to EnergyKey and displays energy consumption to end-users, in this case BYGST's tenants. Since IWMS is master on building data and EMS on consumption data, a two-way application programming interface is developed for data exchange.

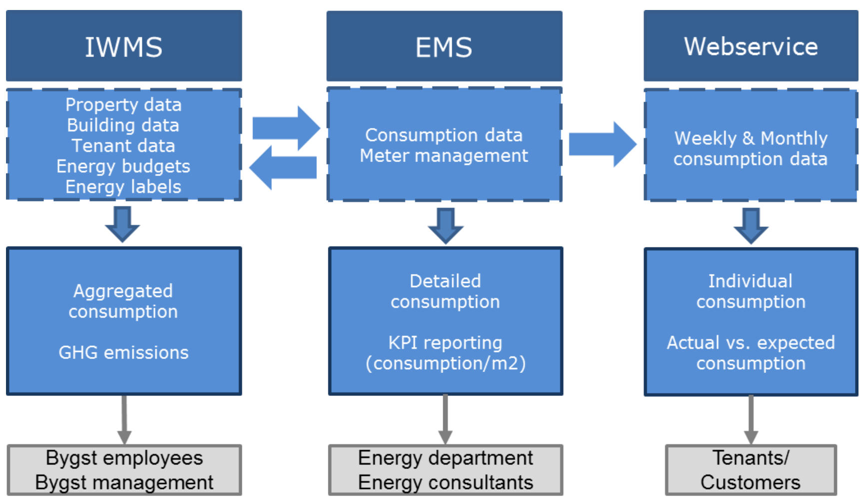

Figure 2: Energy management model at BYGST. (based on system design document)

Energy management reports electricity (kWh), heating (kWh) and water (m^3) consumption on different building levels (property-building-lease unit) and for different tenants.

EMS is internally used by BYGST's Energy department and operates as an engine for meter management and consumption readings. It provides deep insight on energy performance in each BYGST lease unit, building and property. The consumption readings in office buildings were earlier collected in different formats, by using data loggers, automatic meter readings and manual meter readings. This reading process caused data inconsistency due to different reading formats, frequency, and technical failures. The 95% of electricity, 65% of heating and 35% of water consumption in office buildings is now delivered directly from the utility companies to EMS through remote readings (Bygningsstyrelsen, 2017b). The remaining consumption is still collected through dataloggers, but will over time be delivered directly from utility companies. The Danish Meteorological Institute delivers degree-day data to EMS daily, and heating consumption is benchmarked right away, regardless of weather conditions.

IWMS is a master system on core data and delivers data on buildings, energy budgets and tenants to EMS. By combining core data from IWMS and own consumption readings, EMS calculates energy consumption for each tenant and provides performance indicators (consumption/m^2) on different building levels. IWMS receives aggregated monthly consumption data from EMS through an interface and calculates greenhouse gas emissions. The monthly consumption and emissions are available to relevant BYGST employees for reporting purposes on the property portfolio.

The tenants have access to the webservice, where they can login and follow their own electricity, heating and water consumption. The tenants can monitor their monthly/weekly/hourly consumption and compare it with expected (last year) consumption.

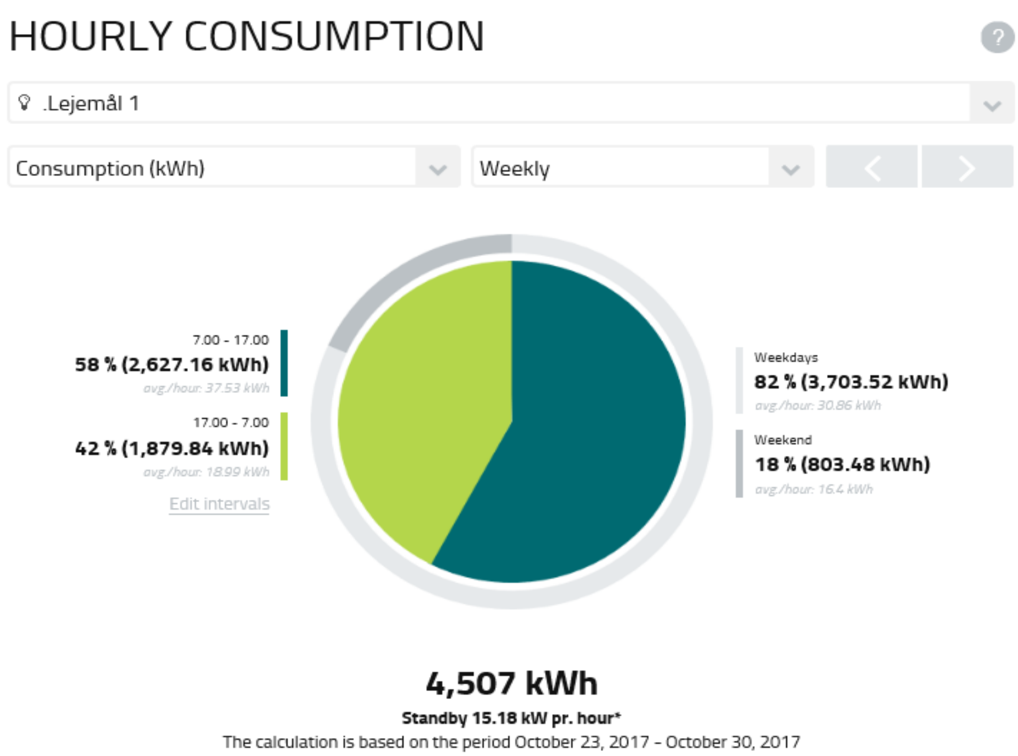

Figure 3: Webservice solution for BYGST's tenants. (Webtools)

Figure 3 shows the webservice solution for weekly electricity consumption for Lease 1 (Lejemål 1) in a multi-tenant office building. The webservice displays consumption for working hours (7.00-17.00), non-working hours (17.00-07.00), and weekends. The associated facilities managers have access to the data and can e.g. observe that 42% of electricity consumption is used outside of working hours, and that 18% of electricity is used in weekends. Since an office building has working hours 7.00-17.00, this information can be useful for identifying potential energy losses. The data is also useful for benchmarking energy consumption between tenants, and for monitoring stand-by consumption.

Another example of how IT systems impact a real estate organisation was observed few days after the deployment of EMS. A facilities manager observed that the electricity consumption in one lease unit was higher than expected during non-working hours. The observation led to identifying defects in some light sensors that were replaced afterwards, and electricity consumption was normalised.

5 FINDINGS AND DISCUSSION

Implementing IWMS plays a key role in the change management process at BYGST. The system is used for internal, mutual adjustment, and aims to create common data platform for BYGST's employees and to deliver better service to BYGST's customers. However, the implementing process is complex since it impacts all three innovation spheres (product, process and organisational innovation). The product (IWMS) is further developed during the implementation and configured to match BYGST's needs. BYGST's business processes are reviewed in parallel, meaning that they can be changed to match the system functions. During the implementation, several key persons from BYGST (e.g. IT project manager, Head of IT department) have left the agency, illustrating unfreezing and movement steps in a change management process. Also planned user trainings demonstrate unfreezing and movement steps since the trainings will change users' IT skills.

Business Process Reengineering characterises the implementation since IT is used for supporting organisational change and focuses on value creating for customers. The implementation supports standardisation of work processes, outputs and skills, and is expected to improve interoperability, transparency and data reliability.

IWMS can support users in solving their tasks and improve business processes, but it can only happen if the system configuration matches the needs of organisation. The system itself is not an off-the-shelf solution, but highly dependent on user inputs during the implementation. On the other hand, real estate organisations must at the same time critically review their business processes, e.g. through BPR.

Due to the scale and complexity, the implementation is still ongoing. The implementation takes long time and underlies the importance of benefit realisation diagrams for tracking, whether the implementation follows the initial plan and delivers planned benefits.

Even though the systems are not fully implemented yet, the results indicate that several goals for energy management are already realised. For example, BYGST and tenants in office buildings have now access to valid energy data, and the agency provides better customer service through the webservice. Savings on energy consumption are also observed. However, the question remains, whether full systems implementation will deliver all, or only some benefits? To which degree will the complete solution fulfil the actual needs of different stakeholders? Will benefits to one stakeholder bring disadvantages to another? This will be investigated further in the follow-up study.

6 CONCLUSION

The implementation of the IT systems IWMS and EMS creates several impacts on energy management in real estate organisations. The study shows that new, exhaustive insights on energy consumption and usage patterns increase focus on actual energy performance across the building portfolio and highlight possibilities for further energy optimisation and energy savings.

IWMS and EMS can provide more standardised data on property management and ensure better overview of actual building performance. The successful deployment is though conditioned by several prerequisites such as availability of internal resources and their competences and clear definitions of which business processes IT systems must support. The IWMS implementation is a complex process involving many different stakeholders and takes long time to complete.

Energy management can be improved when valid core data and consumption data is provided, combined, and properly presented to different stakeholders such as property managers, energy specialists, facilities managers and end-users/tenants.

Further studies will develop an IWMS implementation guide and propose a method for improving environmental building performance thorough IT systems and dynamic data.

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PAPER 4

(P4)

Drivers for IWMS implementation in real estate management

Esmir Maslesa

Per Anker Jensen

ABSTRACT

Purpose: IT platforms like Integrated Workplace Management System (IWMS) gain higher importance in real estate management, but there is lack of knowledge on what IWMS is and what the drivers are for its implementation in real estate organisations. The article aims to provide knowledge on this.

Design/methodology/approach: The research combines theories of real estate management, IT implementations and change management with a qualitative case study of IWMS implementation in a public real estate organisation in Denmark. The research data consists of customer surveys, document studies, semi-structured interviews and in-depth analysis of IWMS features.

Findings: The article identifies several drivers for IWMS implementation such as data standardisation, validation and easier data exchange, business process optimisation, decrease in IT-costs, and improved customer service. Furthermore, the case study reveals that the IWMS implementation is not considered as a definite IT project, but as an organisational change project impacting the entire organisation.

Originality/value: There has so far not been any public real estate organisations in Denmark using IWMS and the knowledge about IWMS in public real estate sector is therefore limited. To date, no one has analysed what the drivers are for IWMS implementation in real estate organisations. This research paper brings new knowledge on IWMS and presents drivers for IWMS implementation observed from an implementation process in a public real estate organisation.

Keywords

IWMS, Integrated Workplace Management System, Real estate management, IT implementation, IT system, Organisational change

Article Type: Research paper

1. Introduction

In real estate management and facilities management, IT software systems can be divided in Data Containers (e.g. FTP servers, databases and BIM) and Workflow Systems (e.g. ERP, IWMS, CMMS and CAFM) (Ebbesen and Bonke, 2014). This paper focuses on workflow system Integrated Workplace Management System (IWMS).

Ebbesen (2015) identified 32 academic articles focusing on IT in facilities management and found that only 7 of them address workflow systems. However, none of the 7 articles on workflow systems focus on IWMS: five articles consider CAFM (Computer Aided Facilities Management) and two CMMS (Computerized Maintenance Management System), indicating a general lack of research on workflow systems, and particularly on IWMS. Furthermore, Ebbesen (2015) also found that only 25% of the articles focus on implementation and use of IT in organisations, while 75% focus on conceptualization and development. These findings highlight the overall need for further research on implementation and use of IT systems in real estate and facilities management.

At this time, there are no public real estate organisations in Denmark using IWMS and the knowledge about IWMS is therefore generally limited. However, the Danish Building and Property Agency (BYGST), who manages 4.000.000 m^2 of governmental buildings, and is the largest public real estate organisation in Denmark, is currently in the process of implementing IWMS, making it the pioneer in the field. This development therefore raises the vital research questions of, what is IWMS, and what are the drivers for its implementation in a large, public real estate organisation?

By studying the case of implementation of IWMS in BYGST and answering the research questions, this article aims to add knowledge on IWMS and the drivers for its implementation in real estate organisations.

In 2004, the American research and advisory company Gartner invented the term "Integrated Workplace Management System" and defined it as an enterprise suite that includes five key components: capital project management, real estate/property portfolio management and lease administration, space and facilities management, maintenance management, and sustainability/ facility optimisation and compliance (Schafer, 2014). A more recent definition describes IWMS as a software platform that enables leaders to manage the whole life cycle of their facilities, helps optimize the use of workplace resources and assists in cost containment by monitoring the real estate portfolio (Gartner, 2017). The IWMS is based on a single database platform through which multiple business processes are interconnected. This ensures easier management of information and increased interoperability since the core data comes from the common database, as illustrated in Figure 1.

In the European context, IWMS comes very close to the understanding of CAFM (Madritsch and May, 2009). However, the major difference is that CAFM mainly focuses on facilities management, space management and maintenance management while IWMS includes additional features like real estate and lease management, project management and environmental sustainability.

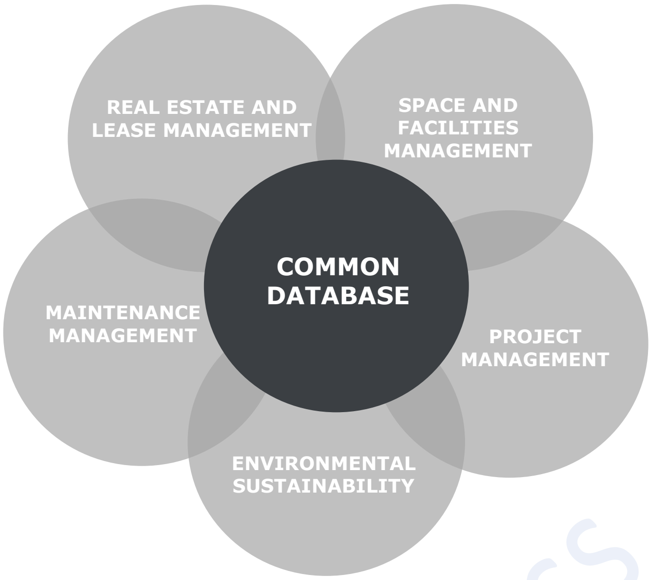

Figure 1: Generic model of Integrated Workplace Management System (IWMS)

Gartner has identified 14 global IWMS vendors, with the majority of them being present in North America and Western Europe (Gartner, 2017). In Denmark, there are at least 13 IT systems available for real estate and facilities management, of which 4 are categorised as IWMS (DFM Network and Basico, 2017). In Danish context, IWMS is considered as the most complex IT system that basically includes all functionalities from CMMS and CAFM, but also modules for financial management, portfolio management, space management and surveys. Some Danish IT providers describe their IWMS products as ERP (Enterprise Resource Planning) solutions, which also highlights the complexity of IWMS solution (DFM Network and Basico, 2017).

2. Method

The methodological approach is based on a qualitative case study of IWMS implementation in a public real estate organisation (Yin, 2014). The Danish Building and Property Agency (BYGST) was selected as a case since the agency was the first public real estate organisation in Denmark to introduce IWMS. The first author is industrial PhD candidate affiliated to the IWMS provider to BYGST and has as such achieved access to the research data presented in the article.

The research data consist of customer surveys, document studies and interviews. Customer surveys are conducted by BYGST and relate to tenants' satisfaction with BYGST's business areas in the period 2014-2017. The research is further supported by document studies of project initiation documents and system design documents.

For deeper analysis of drivers for IWMS implementation, five interviews with BYGST's representatives have been conducted in period May-October 2017. All interviews were conducted by following the same interview template prepared before the interview sessions. The interviews were originally conducted in Danish and were later translated to English by the authors. The interview template included several questions on topics like interviewees' background and BYGST's organisation and real estate management tasks, IT system landscape before IWMS, BYGST's data needs, drivers for IWMS implementation and the implementation process. All interviews have been recorded, transcribed, validated by the interviewees, and in the end analysed by cross comparing the answers on each interview topic. The purpose of the interviews was to gain deeper knowledge on why BYGST has decided to implement IWMS, and which benefits the organisation expected to realise by implementing such a system. The interviews were partly semi-structured and partly structured. Each interviewee was asked open and closed questions concerning the relationship between real estate management and the IT system landscape in BYGST before IWMS implementation. In the open questions, interviewees were asked to describe BYGST's organisation and business processes, and to give their personal view on the IT systems and related challenges before IWMS implementation, as well as their expectations for IWMS. In the closed questions, each interviewee was asked to evaluate specific topics regarding IT systems with grades 1-10, with 1 being low, and 10 high satisfaction. Some of the closed questions were: "What is your evaluation of user satisfaction with current IT systems?" and "How satisfied are you with the data exchange processes between departments through current IT systems?"

The interviewees and their profiles are presented in section 4.3. Their evaluations and citations in combination with BYGST's customer surveys and document studies represent the research data used for answering the research question regarding the drivers for IWMS implementation.

In the following, the paper presents theoretical relationship between real estate management and IWMS in section 3. After theoretical framework, the case study and research data are introduced in section 4, while findings are presented in section 5. Discussion of the findings is in section 6, and conclusions are drawn in section 7.

3. Theory

3.1. Real estate management

Real Estate Management (REM) is very dependent of the context, where it takes place. In a commercial setting with a focus on real estate investments in property for renting out and/or selling, the aim is to get the best possible return on investment in the short and long run (van der Voordt;, 2017). This is not in focus in this article.

The situation is very different, when REM concerns the real estate to be used by an organisation. This is commonly called Corporate Real Estate Management (CREM). CREM focuses on alignment of real estate to corporate needs and objectives, incorporating the needs and wishes of shareholders and different stakeholders on strategic, tactical and operational levels (van der Voordt, 2017). Dewulf et al. (2000) define CREM as "the management of a corporations' real estate portfolio by aligning the portfolio and services to the needs of the core business (processes), in order to obtain maximum added value for the business and to contribute optimally to the overall performance of the corporation" (Dewulf et al., 2000).

Concerning public real estate, i.e. real estate owned or rented by ministries, municipalities and other governmental agencies, the term Public Real Estate Management (PREM) is sometimes used as a parallel to CREM in private corporations. A Dutch PhD-thesis from 2002 concerning PREM noticed a shift was going on from decentralised real estate management with a focus on facilitating primary processes towards integration of FM and CREM in centralised shared services (van der Schaaf, 2002).

CREM is both as an academic discipline and a profession in practice closely related to Facilities Management (FM). Van der Voordt (2017) has made a comparison of CREM and FM. According to this, CREM has its foundation in asset management, facility management and cost control and its alignment to general management, while FM is characterised by its focus on non-core business services, workplaces and their management. Another difference is that CREM has its focus on real estate as physical and economical assets utilized by an organisation, while FM has a wider service focus, including demands related to space and infrastructure as well as people and organisations (van der Voordt, 2017). There is a trend towards CREM and FM becoming more integrated and converging, which for instance is expressed by the publication of a recent book concerning FM and CREM as value drivers (Jensen and van der Voordt, 2017).

In this article, we mainly use the term real estate management understood as management of public real estate by a state agency, who owns and lets out real estates to other public organisations. This has been the main responsibility for the case organisation BYGST. However, in 2017 BYGST also got the responsibility to procure and provide facilities services to the public user organisations, who rent space from BYGST. Therefore, in the future BYGST will become responsible for both PREM and FM.

3.2. IWMS in real estate sector

Each real estate includes physical systems like heating, lighting, plumbing and ventilation. The same real estate also includes human systems (how occupants use the space) and assets and equipment that people need to perform their jobs. All these systems interact with each other and must be integrated. Therefore, there is a need for data on how each system is working in relation to others (Short, 2017). Having access to facts and figures is not enough. The IT systems must provide deeper insight on the data presented on the users' computer screens. The data analyses must be easy to understand, visually stimulating, accurate and convincing (Sandquist, 2015). This is where an IWMS shows its value, since the system allows integration of relevant business processes.

Hanley and Brake (2016) consider IWMS as a technology solution that can help organisations to record, measure, manage and optimise assets (built assets, fixed assets, mobile assets, asset systems and people) and their complex inter-relationships, which are only becoming more complex in the advent of the Internet of Things (IoT) and Big Data.

IWMS operates with relational datasets meaning that a work task is linked to data records for the associated employee, assets, and procedures. The first step, when implementing IWMS, therefore is to link the organisational records with resources such as people, locations (site, property, building, lease unit), assets, geographical and organisational hierarchies, and cost codes. A strategic and structured approach is required when implementing an IWMS (Hanley and Brake, 2016). The criteria for successful implementation seem to be planning, expectation setting and managing the change within the organisation (Gibler et al., 2010). A phased implementation is considered the most efficient approach. The clients should start with whichever application that delivers the most immediate value to the organisation. Depending on the system configuration, IWMS can provide functionality to support best practice management of business processes relating to workflow management, project management, lease management, environmental reporting and asset management.

A key benefit of an IWMS is that it uses the same underlying data set, whether it concerns assigning a maintenance work task, scheduling a project, or disposing of an asset (Hanley and Brake, 2016). With the right information, the system can perform useful actions without human interaction and thereby save some labour costs, or, it can assign a task to an employee that can perform a certain task and prevent a costly failure, if something is wrong. When it comes to the process of capital planning from lifecycle and management of facilities perspective, IWMS can help buildings owners to understand, what projects need to be prioritized and funded (Short, 2017).

Because of its size, complexity and functionality features, IWMS is mainly recommended to real estate organisations that usually manage large portfolios (over 100.000 m^2) across several locations. Real estate organisations with few properties might have better benefits from implementing CAFM or CMMS. Typical IWMS users are corporate real estate managers, facilities managers, maintenance managers and environmental/energy managers and their teams. Top management can use IWMS for strategic reporting on capital projects, maintenance tasks, space utilization or energy efficiency benchmarking.

Historically, the main driver for implementing an IWMS solution was cost management. Managing facilities expenses is still an important consideration, but providing a flexible workspace, where people want to work, has increased in importance. For example, a recent study conducted by Gartner shows that employees' work environment has a significant impact on their effectiveness and engagement, yet only 34% of workers like their workspace (Gartner, 2017). Another aspect is that employees in the REM sector spend a lot of time in the field and need to be able to bring and complete their tasks remotely. IWMS supports these needs since the technology is available on different products (tablets, smartphones) and mobile apps.

There are several global companies that use IWMS. General Electric (GE) implemented an IWMS as part of a global restructure of its portfolio. The implementation supported significant cost savings and reduced operational costs. Nokia implemented an IWMS to manage its portfolio, which was previously managed in 65 different systems. The implementation reduced real estate portfolio of more than 278.700 m^2 and operational costs by 500 million Euro, and reduced energy consumption by 7% (Hanley and Brake, 2016).

An UK government organisation managed real estates with siloed business processes through over 70 siloed systems. An IWMS implementation led the organisation to directly interface with commercial, financial and personnel systems. This has improved data quality, enabled better financial forecasting, introduced procurement savings, reduced maintenance costs and significantly reduced support costs of legacy systems (Hanley and Brake, 2016). One of the key lessons learned from this case was that the successful implementation was dependent on a pace of change that the organisation and its employee could support, particularly reflecting that business process and data governance needed a step change to evolve with the new technology.

For larger real estate organisations, an IWMS brings much greater benefits than using several stand-alone applications. Hanley and Brake (2016) claim that organisations that have implemented an IWMS have experienced significant operational benefits, through more efficient business processes, better stakeholder relationships, reduced operating costs, improved productivity and clear demonstration of legal compliance. With a single data repository, transparent reference data, and comprehensive analytics, organisations can embrace a new generation of key performance indicators to command differential advantage in their competitive environments (Hanley and Brake, 2016).

4. Case study and data collection

4.1. The Danish Building and Property Agency – Bygningsstyrelsen (BYGST)

BYGST is the Danish state's property enterprise and developer, whose main task is to provide work spaces and office and research environments on market terms for its customers, including universities, central administration, police and the courts. BYGST was established in October 2011 as part of a Danish governmental formation. Several governmental agencies (part of the Agency for Palaces and Properties, University and Building Agency, Business and Construction Agency) have been consolidated into BYGST, and the agency is still undergoing organisational changes. BYGST solves its task by owning and renting out buildings of the state through new construction and modernisation, and by redistribution of private leases to the state institutions. The agency has about 300 employees that manage 1.800 leases covering more than 4 million m^2 of building area. About 1,2 million m^2 are private leases and public-private-partnerships, 2 million m^2 are used by the universities, and approximately 800.000 m^2 are office buildings owned by BYGST (Bygningsstyrelsen, 2017).

The current IT system landscape is diverse due to former reorganisations, different employee needs, working cultures and local IT-solutions emerged over many years prior to the consolidation. The IT system landscape is a product of long-term accumulation of silo-based systems that support individual needs of different departments at BYGST. Several IT systems contain the same type of data that is updated individually in each system, leading to missing coordination and poor data quality (Anonymous, 2018). BYGST therefore needs a more consolidated IT system landscape that can reduce the amount of IT systems and secure consistent, valid data across the entire organisation. For solving the problem, BYGST visited several real estate organisations using IWMS outside Denmark (The Dutch Building and Property Agency and 4 companies/municipalities in the UK). Based on the experiences and recommendations from a market survey, BYGST decided to introduce IWMS (Bygningsstyrelsen, 2015). The internal need analysis and the market survey was initiated in 2012. The tendering and contract sign-off took place in 2016. The implementing process (design-build-test) was initiated in early 2017 and runs till the end of 2018. The implementation involves four organisations: BYGST as a customer, an external consulting company engaged to support the implementation, the IWMS provider (national IT company selling the IWMS in Denmark on license), and the IWMS developer (multi-national IT company that has taken over the company, who has originally developed the IWMS). The official implementation team includes 35 people of which 14 are from BYGST, 12 from the external consulting company, 5 from the IWMS provider, and 4 from the developer. Moreover, there are additional personnel involved in the implementation as needed.

BYGST has a vision of being the preferred property manager for customers and the state. The strategic goal is to build up a strong, data-driven knowledge organisation concerning work spaces and efficient building processes, construction and real estate management. A stronger, data-driven knowledge organisation is expected to create the basis for advising and decision-making that will result in cost effective solutions for the agency and their customers (Bygningsstyrelsen, 2012). By introducing IWMS, BYGST wants to combine data, knowledge and professional experience to change the organisational configuration and deliver improved customer service.

Recently, BYGST got responsibility for providing FM services to their tenants by outsourcing as mentioned in section 3.1, but this business area is still under development at BYGST and therefore not covered by this article.

4.2. Customer surveys

Every year BYGST conducts a survey on tenant satisfaction with core business tasks provided by BYGST. The survey is distributed to tenants across universities and state properties (private leases excluded) and measures general satisfaction with BYGST's portfolio management and six specific business areas provided by BYGST. The 2017 survey contained 515 responses. The grades ranged 1-5, with 1 being lowest and 5 highest satisfaction. The tenant satisfaction within six specific business areas for period 2014-2017 is presented in Table 1.

Business area	**2014**	**2015**	**2016**	**2017**
Operation and Maintenance	3.8	3.7	3.7	3.8
New construction, modernisation and reconstruction	3.8	3.6	3.6	4.0
Moving	3.7	3.5	3.6	4.4
Rent Collection	3.7	3.5	3.7	3.6
Energy Consulting	3.3	3.1	3.4	3.4
BYGST as developer (new)	-	-	-	3.8

Table 1: Tenant satisfaction with BYGST's business areas across universities and offices (excluding top managers).

The general tenant satisfaction with BYGST's real estate management was 3.6-3.7 in the period 2014-2017. Moreover, the table shows that, in 2017, the tenants were most satisfied with BYGST's service on moving projects and that tenants' satisfaction with BYGST's handling of new construction, modernisation and reconstruction projects has increased. On the other hand, the tenants were least satisfied with rent collecting and energy consulting services. Among all six business areas, tenant satisfaction has generally been the lowest with energy consulting services in the period 2014-2017.

4.3. Interviews

During the system implementation, five semi-structured interviews regarding drivers for IWMS implementation have been conducted. The interviewees were selected based on their function and business area at BYGST as shown in Table 2.

Function	Years at BYGST	Business area	Interview date	Interview duration
IT senior consultant	4	Project management, IT and business strategy, change management	19-05-2017	01:30:49
Technical consultant	6	Energy management	06-06-2017	00:53:34
Head of IT dept.	4	IT systems and data	16-08-2017	00:56:56
Head of Building dept.	6	Buildings, Construction	18-08-2017	01:18:43
Head of Lease dept.	6	Lease management	03-10-2017	00:53:14

Table 2: A list of interviewees and details of each interview.

The IT senior consultant has background in computer science, finance and change management and is responsible for project management regarding IWMS implementation. The technical consultant has background in engineering and is responsible for energy management of BYGST's properties. The head of IT department is a Master of Business Administration and has been working with IT in public organisations for 30 years. He is responsible for IT systems and data at BYGST. The head of Building department is a Master of Public Management and is responsible for operation and maintenance of BYGST's properties. The head of Lease department is an economist responsible for lease management department at BYGST.

5. Findings

5.1. IT system landscape at BYGST

Each interviewee could evaluate eight specific topics on BYGST's IT system landscape before IWMS implementation with grades 1-10, with 1 being low, and 10 high satisfaction with the existing IT processes and solutions. The results of their evaluations are shown in Figure 2.

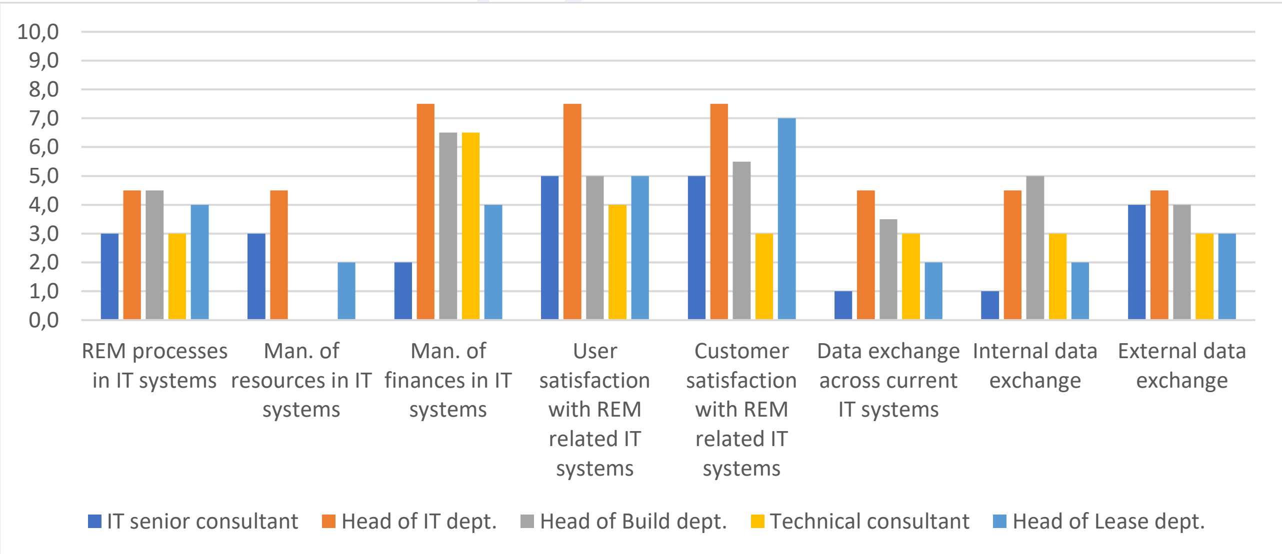

Figure 2: Evaluations of BYGST's IT system landscape before IWMS.

The interviews revealed several challenges related to the IT system landscape before IWMS implementation. Some of the biggest challenges were related to data exchange. When asked to describe the data exchange processes between IT systems before IWMS, the head of IT department explained:

"*Partly, we have redundant data, partly we have a maintenance work that is greater than it should be because they are redundant, and partly we have challenges in compiling the data across the organisation because the definitions in the individual systems are not necessarily the same."*

Data exchange across existing IT systems obtained the lowest average score (2.8) because of the missing system integrations and use of different data formats. Furthermore, due to missing system integrations, internal data exchange processes obtained the second lowest average score (3.1) while data exchange processes with external users had the third lowest score (3.8). Consequently, BYGST faced challenges in managing processes and resources related to PREM since the data inconsistency made it difficult for the organisation to have a proper performance overview across entire real estate portfolio.

However, Figure 2 also shows that the interviewees at the same time evaluated user satisfaction (BYGST's employees) and customer satisfaction (e.g. tenants) with the current IT systems to be high relative to other topics with average score of 5.3 for the users and 5.6 for the customers. These findings contrast with previous findings regarding data exchange, and the head of Lease department tried to explain:

"I think they have learned to live with the systems. They may see the systems are not optimal, but you must get the best out of them. This is sometimes the case. Live with it."

Regarding the IT systems, all five interviewees estimated that BYGST used more than 10 different IT systems for supporting REM. The IT system landscape included FM systems (CAFM), standard IT systems like MS Office and Outlook, department-specific systems used for accounting, lease management, energy management, and some employees even used hand notes. When asked to describe challenges with current IT systems and drivers for IWMS implementation, the head of IT department explained:

"We have maybe 25 IT systems that exist separately, and they are also being maintained to some extent individually. Of course, it is always problematic to start compiling the data to create a foundation that goes across some disciplines. It is a big issue for us. That's why we want to put all these IT systems into IWMS, concentrate on one, common database so when we make decisions, they are on the same basis, with the same understanding of what these data are expressions of, and that we are actually sure that the same decision-making basis is present before and after."

The technical consultant also gave his view on BYGST's IT system landscape and reasons for implementing IWMS:

"We cannot keep on having 20, 15, or how many IT systems there are now. There must be something as basis, just because there are so many factors going through - areas, customers, users - and it needs to be maintained. Unless we have one platform where we can have basic information, it's hard to make use of economies of scale and run things cross-sectionally. That is the reason why we need one common system. Also, to be able to maintain it."

According to the IT senior consultant, one of the benefits by implementing IWMS is that this system solution can provide synergies between different business areas in REM:

“If you have better facilities management, combined with better lease management and other things, it will be easier to find out which properties you should phase out, which properties you should keep, and which synergies are coming out of that, instead of keeping most of it in Excel sheets so that much information is lost, because many decisions are not based on a professional basis, but on a more personal basis.”

The above statements draw parallels between BYGST and an UK government organisation that earlier used over 70 siloed systems for REM. In an UK case, Hanley and Brake (2016) found that the IWMS implementation has improved data quality, reduced maintenance costs and significantly reduced support costs of legacy systems – some of the issues that the interviewees also expect IWMS can solve for BYGST.

5.2. IWMS implementation process

Regarding the implementation process, all interviewees agreed that the implementation of IWMS should be considered as an organisational change process rather than a definite IT project. For example, when asked to give his view on the IWMS implementation process, the IT senior consultant stated:

“I see it as a change management project. I have always done that. From day one, I have always said that it is a change management project. If we run this as an IT project, it will never be a success.”

Head of IT department gave a similar view on the implementation process:

“The IWMS (implementation) process at BYGST is NOT an IT project. It is an organizational change project that is tool-supported by technology. It is important to understand. Technology is the lever of the organizational change in which we change procedures, rules and contexts to make things more consistent than they are today.”

Also, the technical consultant expressed his thoughts on the implementation process:

“An IT project is worth nothing unless you can get someone to manage it and follow your organisation. There are a lot of processes, workflows and conversions that have to be done internally to succeed."

Another important finding regarding the implementation process is the implementation period. The initial thoughts on IWMS implementation started to flourish at BYGST in 2012 while the actual implementation started in early 2017 and runs till the end of 2018. Regarding the implementation period, the head of Lease noted:

“I think I have heard about this system for almost three years, and it is first now that we are making design documents. That is where we are now, three years after. I do not know if it is normal that it takes so long, but I think it is a long process. One could say it is a long process for the employees to be in.”

5.3. IWMS solution at BYGST

BYGST has decided to implement five IWMS modules to their organisation: Core, Lease, Project, Customer Relationship Management (CRM), and Energy module. Table 3 provides brief overview of main functionalities of each module.

IWMS module	Main functionality
Core	Delivering and maintaining data on properties, buildings, floors, rooms, units Delivering and maintaining data on building owners, tenants, suppliers
Lease	Managing lease contracts, rent processing, service charge processing, deposits, etc.
Project	Documenting and managing construction, renovation and modernization projects
CRM	Documenting and processing requests and questions from the customers/tenants
Energy	Energy management – electricity, heating and water consumption reporting Energy dashboards

Table 3: IWMS modules and their functionality areas at BYGST.

Besides the five IWMS modules, the design solution also includes four integrations with other IT systems and databases. The integrations cover 2-way integrations with Energy Management System (EMS) and financial system, and 1-way integrations with central building database based on Object-oriented Input System (OIS) - OIS is the master, and an IWMS integration with project collaboration platform for construction industry.

In the following, a more detailed description of each IWMS module from Table 3 is given, as well as some drivers for their implementation.

5.3.1. Core module

The Core module manages data relating to properties, buildings and their users. The module is based on the OIS database delivering data on building owners and tenants, property/building number, address, area size of various types, cadastral area, year of construction etc.

The main requirements of the Core module are the ability to hold portfolio information on all building types, to store different types of records (buildings, floors, rentable units), to store records by key elements and be able to link elements together, e.g. link rooms to floors. Furthermore, the module is used for creating leases in order to generate rent/service charges and allow supplier records to be added for entering invoices. The Core module provides also ability to store related documentation, e.g. floor plans, energy information, building information so that all personnel can view all details (subject to security).

Securing valid core data about buildings and tenants was also in the IT senior consultant's focus, since BYGST has been struggling with data consistency and validity for a long time:

"Now, it is only about acquiring valid data. We are completely down there where we want valid data. Just getting valid data, it is a huge development. But it is not that far to the other things once data is in place."

Additionally, the head of Building department specified the following issues with data relating to buildings and their users:

"I do not think it is easy (to share the data) with existing IT systems. It is on the economy side because we run the same system. But at the task level, it is hard to do. There, it is often that we need to extract some summaries to Excel sheets if they need the information."

These statements explain the importance of data in REM and highlight some of the issues regarding data management at BYGST. Furthermore, as pointed out by Sandquist (2015), the data analyses must be easy to understand, visually stimulating, accurate and convincing, which BYGST expects to achieve through IWMS implementation.

5.3.2. Lease module

The Lease module manages processes relating to tenants and lease administration. Tenant's cycle covers moving in and out phases and the period of actual lease agreement. Moving-in phase includes creation of a lease contract, first time charging and moving-in report and lease agreement. During lease period, administration processes regarding rent collection and notifications, regulation of deposit, regulation of lease area, consumption settlement and warnings of new rents, taxes and charges are handled in Lease module. When moving out, the module is used for registering lease termination, sending termination confirmation to the tenant, creating and sending moving-out report and move statement. According to the head of Lease department, IWMS can bring two benefits for lease management:

"There are two things I want from IWMS: I want that my department becomes more effective in their workflows, meaning that they use less resources so that they instead of doing things three times only do it once. And I also hope that the system will make it more flexible to help customers more, among others with forecasting. They ask about many things that they would like to have: e.g. budgets, but we cannot help them since it is a manual process and we have to use a lot of resources on that, but we don't have time. In that way I hope that we will be able to make our customers happier and be more flexible in relation to them."

5.3.3. Project module

As governmental real estate organisation, BYGST currently runs construction projects for almost 1.3 billion Euro. In relation to that, BYGST wants to hold information for major construction projects, tasks and associated costs in one place. Furthermore, the agency also wants full visibility of project documents for internal and external users.

The Project module in IWMS allows BYGST to record new construction projects, their milestones and documentation. Projects in IWMS are used to record when a request has moved out of the CRM cycle and passed to the project management team. IWMS can hold financial information against a project e.g. budgets, templates, etc. with full email authorisations and approval process.

The main goals for the Project module are to replace existing project tool for high level project portfolio management, reduce amount of project data for registration, add missing data that cannot be delivered by the existing project tool but is demanded by BYGST, and implement simple methods for registration of key project data (i.e. few reporting fields, as much automated data entry a possible, as few advanced or complex features as possible).

5.3.4. CRM module

The CRM module is used for processing and documenting all requests, questions, complaints etc. coming from the current or future tenants of the buildings in the BYGST's portfolio. This module is used for holding all relevant information and discussions regarding customer relationship management in one place.

During the implementation workshops, it was found that there is a significant number of cross-module functionalities related to the customer relationship management. The CRM module will therefore have dependencies on other IWMS modules that BYGST implements.

5.3.5. Energy module (environmental sustainability)

Prior to IWMS implementation, BYGST has been struggling with data validity on energy consumption, correct baseline estimation and performance benchmarking across property portfolio. All these issues are closely linked to the customer satisfaction surveys from section 4.2 in which energy consulting generally has had the lowest customer satisfaction over several years. For example, the tenants have especially been complaining about erroneous energy invoices and missing access to their consumption data. Some of the issues with poor energy management were also specified by the head of Building department:

"The (old IT) system was based on data loggers installed on the meters. There were many errors with them. The errors consisted of wrong installations, e.g. if data loggers did not match the meter, if the meter was set up to different factor, then incorrect numbers were reported. For example, it could also happen that the utility companies went out and changed the meters without informing us, and if we did not detect it, there were errors in data. So, our old IT system was challenged by the fact that there were many data holes in it."

For solving the issues with poor energy management and improving environmental sustainability of its portfolio, BYGST has decided to use the IWMS Energy module. However, during discovery phase for IWMS implementation, the IWMS module alone was considered not to be sufficient to fulfil all BYGST's requirements on environmental sustainability monitoring and reporting. The Energy module is therefore supported further by an Energy Management System (EMS) solution through an interface that can deliver deeper insight on energy performance. The EMS solution is a separate IT system delivered by the same provider as the IWMS.

Currently, the new energy management model is partly up and running through the EMS, but there is no full integration with the IWMS yet. The EMS as a stand-alone solution enables relevant stakeholders (energy managers, facilities managers and tenants) to access validated hourly-resolution data which enables to track changes and the effects of energy-saving measures or other interventions. The head of Building department expressed his opinion on the new model:

"Today we measure directly on consumption meters (through EMS), and we collect data directly from the utility companies in most places. One can say it is settlement data, they cannot be wrong because it is the same data as you pay for."

On new energy management model and its benefits, the head of IT department stated:

"Now we have some values where we within few days can see whether it changes something that we turn up or down the radiator, instead of waiting for a month and maybe being able to interpret some result. Now we can see a direct causal relationship between an activity and effect. It gives us another opportunity, partly to energy optimize, but also to guide customers in the correct use of a building. But also to do damage control significantly faster, if suddenly something happens so the consumption peaks, because we get these hourly values. Previously, we got some data values with significantly longer intervals.''

The entire design solution for new energy management model at BYGST and the benefits of EMS are further described in Anonymous (2018).

6. Discussion

Our study shows findings similar to earlier research on IWMS implementations (e.g. Hanley and Brake 2016), but it also indicates a potential difference in drivers between PREM and CREM organisations. For example, Hanley and Brake (2016) showed that global CREM organisations mainly implemented IWMS with focus on cost reductions. On the other hand, our study indicates that PREM organisations might have other reasons for implementing IWMS. The main drivers for implementing IWMS in this study can be classified as quality improvements of internal business processes. For example, BYGST has decided to implement five IWMS modules to support their organisational change process. The agency decided to move away from a silo-based organisation and build up a knowledge-based organisation in which the employees use the same core data for solving their tasks.

Based on the findings from interviews and document studies, several drivers for implementing IWMS at BYGST can be identified. Some of the main drivers relate to data standardisation, validation and easier data exchange across departments and with external users. Other drivers cover faster execution of business processes, time savings and resource optimisation, better interoperability between departments, and savings on IT costs.

BYGST has been using and maintaining the same data in various IT systems, which over the years led to data inconsistency and missing overview of the actual performance across building portfolio. Especially challenges with the building area data were observed. During the implementation, it was found that BYGST was using up to 15 different building area types (e.g. gross/net area, lease/contract area, heating area, drawing area, common areas etc.) which were mainly stored and updated in single point systems, without strategic coordination of data maintenance. When implemented, IWMS will be able to handle all these building area types in one place, ensuring that any changes in area data become immediately valid across the entire organisation. Moreover, IWMS will enable easier data exchange across departments since all employees will have access to relevant data through specific IWMS modules. As a PREM organisation, BYGST is interested in strategic reporting and benchmarking of its buildings on different KPI's, and this is where data exchange really shows its value. However, to be able to conduct strategic reporting and benchmarking, basic business processes and data types must be standardised so there is a clear understanding of how the output is achieved. Standardising the data and improving data exchange processes through IWMS implementation cannot happen without help. The implementation must happen in parallel with business process reengineering in which workflows related to data needs, data collection, handling and analysis are mapped, reviewed and adjusted accordingly. This approach justifies, why IWMS implementation is not perceived as a definite IT project by BYGST, but as the organisational change process.

Single point systems like CMMS or EMS have a high degree of customization for a specific need. They may be more specific to each department's concrete needs, but they also have limited cross-functionality that is required by large REM organisations. Choosing IWMS may reduce possibility of fulfilling all department-specific needs, since all processes are aggregated in a single system. In this way, the possibility to individualise specific business processes becomes lower with an IWMS solution compared to the single point systems. On the other side, IWMS can be configured to match more strategic needs of an organisation. This is especially valuable for larger REM organisations that require certain level of standardisation across the entire organisation. Furthermore, since IWMS features many cross-functions, the system can be used to replace several single point systems, resulting in potential savings on IT costs. This situation was observed in energy management, in which the old data logger system was replaced by EMS and the upcoming IWMS interface. However, this particular design solution has also revealed certain limitations in IWMS. For example, the IWMS Energy module was not sufficient to cover all customer's needs on environmental sustainability reporting. The Energy module is therefore supported by a single point system, EMS, which delivers deeper insight on energy management of BYGST's properties.

The organisation of IWMS implementation at BYGST, as described in section 4.1, is a clear expression of project complexity. The implementation includes risks of conflict of interest and collaboration issues since more than 35 people from four organisations are involved. While the external consulting company is responsible for change management at BYGST, the IWMS provider and developer are focused on delivering the appropriate IT solution for the customer, whose organisation and needs for the IWMS in the meantime might be changing. To exemplify, during the implementation, BYGST has changed the CEO twice, and two of the interviewees deeply involved in IWMS implementation are no longer employed at BYGST (Head of IT department and IT senior consultant). Moreover, BYGST has, as mentioned in section 3.1 and 4.1, recently also got responsibility for providing FM services to their tenants, which means that the implementation now also must relate to the development of a new business area. To support this organisational change, BYGST has subsequently decided to implement the IWMS FM module in the near future. This integration of FM and REM in centralised services supports earlier findings by van der Schaaf (2002).These organisational changes clearly demonstrate that the IWMS provider during the implementation needs close collaboration and continuous input from the customer to ensure proper system configuration that matches the actual needs of the organisation. On the other hand, the IWMS customer, besides financial costs, must be prepared to invest time and human resources in the implementation process to get the desired solution. The implementation must include goal setting and user involvement, and be able to manage organisational changes, as highlighted in Gibler et al. (2010). This might particularly be a challenge for smaller REM organisations with limited resources, and partially explain, why mainly larger REM organisations decide to implement IWMS.

7. Conclusion

An Integrated Workplace Management System (IWMS) is a technological platform that combines relational data records for the building stakeholders (employees, managers, tenants, suppliers etc.), assets (built assets, furniture, equipment) and business process (workflows) to deliver a deeper insight on real estate management across the entire organisation. The strength of IWMS is that its modules rely on a common database which contains essential information on the building stakeholders and assets, so the entire organisation uses the same data foundation in diverse business processes.

An IWMS is mainly implemented in larger real estate organisations that are used to work in silos and use multiple IT systems to manage their real estates. While earlier research has shown that global CREM organisations mainly implemented IWMS with focus on cost reductions, our study indicates that PREM organisations can have other drivers for implementing IWMS. Drivers for implementing IWMS in this study were identified as quality improvements of business processes with the aim of establishing more knowledge-based organisation. The main drivers observed, in order of priority, are: data standardisation, validation and exchange; faster execution of business processes; time savings and resource optimisation; better interoperability between departments; and savings on IT costs.

An IWMS can be configured to match the needs of a REM organisation, but the system has also certain limitations. Our study has disclosed that BYGST's requirements on environmental sustainability were not sufficiently covered by IWMS features and that the system needed to be supported further by an EMS solution. However, the implemented EMS solution, that later will be interfacing with IWMS, already delivers more standardised energy consumption data, time savings and faster execution of business processes related to energy management.

The IWMS implementation is a complex process involving many different stakeholders inside and outside of an organisation and can take several years to complete. The IWMS implementation should not be perceived as a definite IT implementation project, but as the organisational change process involving different stakeholders across the entire organisation. The successful rollout of IWMS is therefore conditioned by several prerequisites such as availability of internal resources and their competences during the implementation process, stepwise strategic implementation, and clear definitions of which business processes the new system must support.

A point of discussion for further research might be management of environmental sustainability through IT systems. Moreover, there is a need for further research on the relationship between IT systems in use and the portfolio size, and how more recent IT solutions and technological developments like IoT and Big Data modelling can enhance REM.

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PAPER 5

(P5)

Facilities

Managing environmental building performance through IT systems

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Managing environmental building performance through IT systems

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ABSTRACT

Purpose: The paper aims to disclose the role and features of various IT systems for environmental building performance (EBP) in facilities management.

Design: The research focuses on IT systems used for facilities management in four organisations. The research is based on a maximum variance case study in which the selected organisations have different organisation type and portfolio size. Three organisations are from Denmark and one is from United Kingdom.

Findings: Several IT systems can be used for managing EBP. EBP in IT systems is primarily reflected through energy management, with specific focus on monitoring and reporting electricity, heating and water consumption. Furthermore, greenhouse gas emissions related to energy consumption can be calculated in some IT systems, while other environmental categories like building materials and recycling potentials are not adequately supported by the systems covered in this study. Some IT systems offer additional features relating to EBP, such as waste management and space management, but the study shows that these features are not demanded at the current point.

Originality/value: This research contributes with new knowledge on how IT systems are used in different organisations for managing EBP. The paper also shows how various IT systems can add value to real estate organisations and facilities management departments and support their business processes relating to EBP.

Keywords: Environmental building performance, Sustainability, IT system, IWMS, EMS, BMS

Article type: Research paper

1. Sustainability and environmental building performance

Sustainable buildings, green buildings, smart buildings. Nowadays many terms try to communicate that some buildings are better performing than others, when it comes to their environmental sustainability. Yet, the statistics show that the buildings and building construction sector combined consume 36% of global energy consumption and induce nearly 40% of total CO_2 emissions (International Energy Agency, 2017). Moreover, a deeper look at the buildings' environmental performance in a life cycle perspective shows that the use stage of older buildings is typically responsible for 80-90% of environmental impacts, while newer, more "sustainable" buildings have lower operational impacts at the expense of higher embodied impacts during building construction indicating burden shifting tendencies between life cycle stages (Sharma *et al.*, 2011; Cabeza *et al.*, 2014).

Assessing sustainability in buildings is not an easy task and must include all three dimensions (economic, environmental and social) of sustainability. This paper is particularly focusing on the environmental dimension of sustainability and therefore uses the term "environmental building performance" (EBP) to address environmental impacts induced during buildings' operation and maintenance activities. Managing EBP is a complex task since EBP includes several categories that are interrelated. A systematic literature review by Maslesa et al. (2018) identified eight environmental categories that should be considered when managing EBP: energy management, water management, emissions, space management, waste management, building materials, indoor environmental quality, and recycling potential. However, the same study has also discovered that identified environmental categories are not equally represented in research, and that especially energy management and greenhouse gas (GHG) emissions are in focus.

There are various IT systems available for managing EBP in facilities management, but there is a lack of knowledge on how they are used, what their strengths and weaknesses are, and how adequately they cover previously identified environmental categories. Thus, there is a need for further studies within this field. For this paper, we have formulated the following research question: How is environmental building performance managed through various IT systems, and are there any gaps between theoretical environmental indicators and those used in practice?

There is limited research on this topic. Relevant studies of IT systems in Real Estate Management (REM) and Facilities Management (FM) have earlier been conducted by Elmualim and Pelumi-Johnson (2009), Lewis et al. (2010), Gibler et al. (2010), and Ebbesen (2015), but they lack a more comprehensive focus on management of EBP through IT systems. Our paper aims to provide new knowledge on this research topic by answering the above research question.

In the paper, FM is used as the general term for the business area in scope, which also includes the related and overlapping area of REM.

2. Methodology

The research is based on a maximum variance case study in which four different organisations are studied to determine their approach in managing EBP through IT systems. The studied organisations are: The Danish Building and Property Agency (in Danish, Bygningsstyrelsen orBYGST), the national postal company Postnord Denmark, the private IT company KMD, and the educational institution Anglia Ruskin University from United Kingdom. The first author is industrial PhD fellow affiliated with the IT company KMD, which provides IT solutions on the Danish FM market, and has as such gained access to the selected organisations in Denmark.

The studied organisations have different organisational type (governmental, public, private, educational) and portfolio size (between 105.000 and 4.000.000 m^2). The maximum variance case study is selected as a research method for generalisation of results from practice. The research data were collected through eight interviews with representatives of selected organisations. The interviews were conducted in period May 2017 - April 2018 and are listed in Table 1. The interviews were used to gain deeper understanding of the IT context in different organisations, the drivers for implementing IT systems, and their role for managing EBP in practice.

Case study (organisation)	**Interviewee**	**Business area**	**Interview date**	**Interview duration**
BYGST (governmental real estate agency, DK)	Technical consultant	Energy management	06-06-2017	0:53:34
	Head of IT dept.	IT systems and data	16-08-2017	0:56:56
	Head of Building dept.	Operation and maintenance Construction projects	18-08-2017	1:18:43
Postnord Denmark (public postal company, DK)	FM specialist	Operation and maintenance Facilities management	07-11-2017	1:02:35
KMD (private IT company, DK)	Head of FM dept.	Facilities management Hard FM	14-09-2017	0:48:34
	FM director	Facilities management Hard and soft FM	31-10-2017	1:00:13
Anglia Ruskin University (educational institution, UK)	Sustainability engineer	Operation and maintenance BMS	10-04-2018	1:48:59
	Environmental manager	Environmental sustainability CSR reporting	17-04-2018	0:43:54

Table 1: Overview of interviews.

In total, five interviews were conducted with BYGST, but only three interviews are included in this study, since they relate specifically to EBP. The interviews with Danish organisations were originally conducted in Danish and were later translated to English by the authors.

In two cases (BYGST and KMD), besides interviews, field observations and in-depth document studies were used for collecting additional research data. Field observations included participation in several implementation meetings, workshops and on-site observations during the IT implementations. Document studies included background material on the organisations and their business area, their FM departments, and system design documents.

3. IT in Facilities Management

3.1. Information and knowledge management

FM has evolved over time which can be attributed to several important factors from three thematic groupings: i) business environment – including organisational structure, business objectives, and company culture and contextual issues, ii) buildings and facilities characteristics – for example, facility type, location and size, and iii) external interventions/factors – such as business needs and processes, asset maintenance priorities, legislation, and interrelationships with other contractors (Pärn et al. 2017). Thus, accurate, reliable and ubiquitous information is vital for supporting efficient FM. However, the FM sector continues to struggle with information management, mostly due to the peculiarity of information and its fragmentation (Eastman *et al.*, 2008; Pärn et al., 2017). IT systems are therefore needed to manage and consolidate the data and information necessary to make decisions about how to operate and maintain buildings (Lewis et al., 2010).

It is important to distinguish between data, information and knowledge. A collection of data is not information, and a collection of information is not knowledge. Collection of data and information are not usable knowledge, but just collections. Information can be portrayed as the transformation of data, and knowledge as the transformation of information. Therefore, Knowledge Management (KM) can be described as a strategy that aims to develop organisational knowledge through accumulation of organisational data and information, along with past experiences derived from human resources (Dubey and Kalwale, 2010).

KM is a topic that has only been researched to a limited extent in relation to FM. One of the first studies by Pathirage *et al.* (2008) related KM to Intellectual Capital, which they divided in three components: Human Capital, Structural Capital and Customer Capital. The Structural Capital describes the internal structure of an organisation comprising strategy, operating system, physical resources, and work processes of a FM business. The study developed a maturity model of KM in FM with four stages:

1. Recognition of importance
2. Formulation of strategy
3. Implementation of techniques
4. Evaluation of performance

KM is a key source in improving organisational performance (Mutalib et al., 2018). Acquisition of new knowledge is followed by its codification. Codification mechanisms ensure that the new knowledge becomes part of the organisational memory, expanding its reusability in order to deal with future issues similar to past as well as link individuals with beneficial knowledge. IT has a crucial role in the acquirement and codification of organisational knowledge as it can store large amounts of knowledge, allowing its smooth distribution and re-use. Therefore, a robust IT infrastructure to support both the codification and storage of the organisational knowledge is essential. The selection of appropriate technology should be aligned with different organisational aspects. The most important aspect is organisational culture as it is the one that affects internal communication and knowledge transfer, with operational, technical and cost aspects being significant as well (Smith, 2001). The use of IT systems for KM is related to the third stage of implementation of techniques in the KM maturity model by Pathirage et al. (2008). IT systems are essential knowledge repositories for codified knowledge (Davenport et al., 1998).

3.2. IT systems and technologies in FM: overview

IT systems and technologies in FM can be grouped in seven categories, as illustrated in Figure 1 (Ebbesen, 2016). Categories like workflow systems and facilities intelligence systems relate directly to IT systems, while other categories cover technologies and data related to the systems. There is often a strong relationship and dependency across different categories in a FM organisation. For example, workflow systems require input data from data repositories to work properly, and in relation to that, an appropriate interface between the systems and databases must be developed, based on certain exchange standards and protocols.

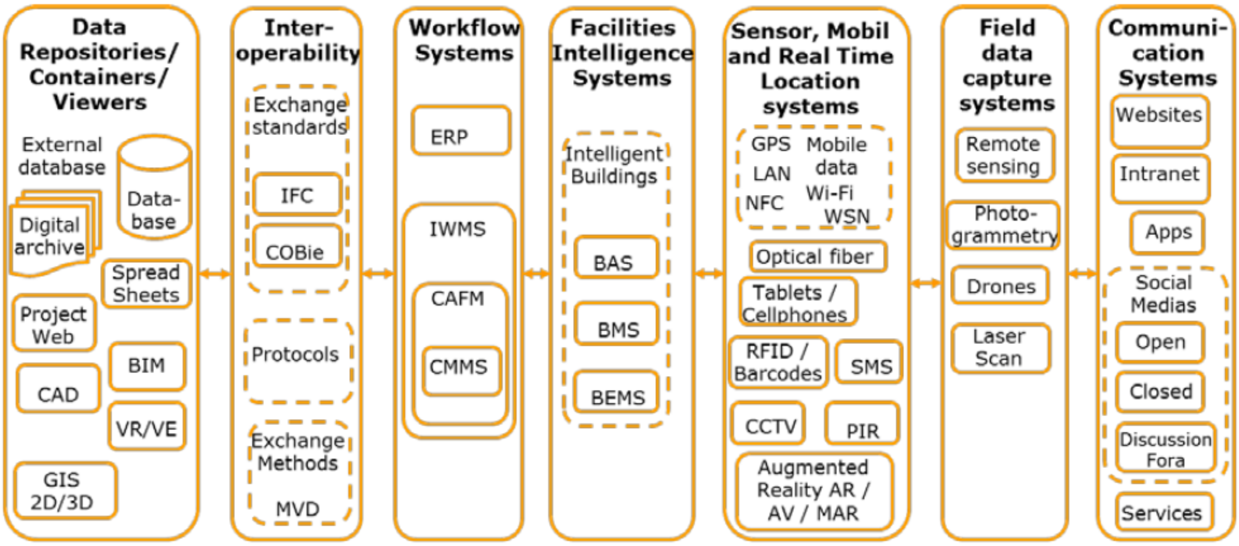

Figure 1: IT systems and technologies in FM (Ebbesen, 2016).

IT systems covered in this research are "workflow systems" and "facilities intelligence systems" since they are primarily used for managing EBP. Workflow systems are, as the name indicates, used for digitising the workflows/business processes related to FM. There are several types of workflow systems in FM, including: Computerised Maintenance Management System (CMMS), Computer Aided Facilities Management (CAFM), Integrated Workplace Management System (IWMS), and Enterprise Resource Planning (ERP).

The core function of a CMMS is to manage information related to maintenance, including but not limited to work orders, asset histories, parts inventories, maintenance personnel management and the calculation of maintenance metrics (Lewis et al., 2010).

CAFM is a tool for organising and managing various activities within the facilities assets and ranges from a simple space management tool to a range of applications such as: maintenance and operations, budgeting and accounting, construction and project management, space forecasting, lease and property management, and asset management (Elmualim and Pelumi-Johnson, 2009).

IWMS addresses a wide range of management needs: financial and lease management, facilities management, space management, project management, and environmental sustainability (Trimble, 2018). IWMS is in research often perceived as, or similar to CAFM (Madritsch and May, 2009; Pärn et al., 2017), while Danish FM practitioners consider IWMS as the most complex IT system that includes functionalities from CMMS and CAFM (DFM, 2018). IWMS is sometimes also associated with an ERP (Lewis et al., 2010). An ERP can be used across an entire organisation to manage all types of information, including corporate finance, human resources, procurement and the functions of CAFM and CMMS. ERP can also be used for energy performance monitoring and benchmarking (Lewis et al., 2010).

Facilities intelligence systems, on the other hand, focus on the actual performance of buildings and their technical installations. Most commonly known facilities intelligence systems are Building Automation System (BAS), Building Management System (BMS) and Building Energy Management System (BEMS/EMS) (Ebbesen, 2016). They are used to monitor, control and manage heating, ventilation, air conditioning (HVAC) and electrical systems in buildings. Their core function is to maintain adequate indoor environmental conditions such as temperature and relative humidity during building operation hours (Lewis et al., 2010).

In this paper, we distinguish between BMS (in Danish CTS) and EMS as they are used for different purposes within energy management. BMS is defined as a system used for digital monitoring, control and management of HVAC and electrical systems in buildings. EMS is a system used to monitor and manage energy and water consumption within buildings. Both BMS and EMS are considered as single point systems as they only relate to one specific business area, in this case energy management.

3.3. Drivers and success factors

Many influential factors from business environment determine the organisation's needs for IT systems. Gibler et al. (2010) found that organisations buy new IT systems for many reasons, but some of the most important include reducing transaction costs, reducing errors, enabling information sharing, formalizing business processes, and increasing processing speed.

García-Sánchez and Pérez-Bernal (2007) found that most of the critical success factors in implementing IT systems were not technical, but included leadership, training, communication, and cooperation. These findings were also supported by a CAFM market survey (GEFMA 940, 2017), which showed that 35% of the implementation costs were direct software acquisition costs, while the remaining 65% were costs associated with data capture and migration, and customisation and user training.

The GEFMA survey showed that the implementation process and the user training are just as important as the software. Also Hanley and Brake (2016) emphasised that the most successful IT implementation depended on a pace of change that the organisation and its people could support, meaning that business process and data governance needed a step change to evolve with the new technology. The difference between successful and unsuccessful implementation seems to be planning, expectation setting and managing the change within the organization more than the quality of any one software vendor (Gibler et al., 2010). Gibler et al. (2010) claim that some real estate department implemented IWMS with excellent results and return on investment (ROI), while other, similar organisations failed in the end due to problems ranging from poor planning to lack of executive business sponsorship and mandate to oversold software and ineffective implementation teams.

Prischl *et al.* (2012) present a method to demonstrate the economic benefits of CAFM implementation based on the concept of ROI drivers. They divide ROI drivers into two groups; (1) ROI drivers that represent and affect typical FM processes such as contract management, maintenance management, portfolio management, and vacancy management; (2) ROI drivers that represent process-independent economic potential, such as transparency, standardization, and the contribution to Corporate Identity. The ROI drivers can have impact on real estate cost, income and asset value. They are measured by a combination of Economic Added Value (EVA = ROI divided by weighted capital cost) and time rate of the return from slow (3-5 years), medium (12 month) to fast (1 month). The results are illustrated in a diagram, where the rate is the x-axis, EVA is the y-axis, and circles placed in the diagram with different diameters represent the potential of the ROI drivers as low, medium or big. The examples in Prischl et al. (2012) include Energy and Environmental Management – also called Utilities Management – but this is regarded as the areas with the lowest potential with medium to low EVA and medium to long time rate of return.

However, the success factors of IT implementation cannot fully be defined and measured in economic terms. An alternative way to measure the success of IT implementation is to apply Benefits Realisation Management. This is an approach usually related to programme and project management, where strategic improvements in business value are called benefits. The creation of business value therefore depends strongly on programmes and projects delivering the expected benefits (Serra and Kunc, 2015).

4. Case presentations

4.1. The Danish Building and Property Agency (BYGST)

The Danish Building and Property Agency (BYGST) was established in 2011 and has more than 300 employees today. BYGST is responsible for managing approx. 4.000.000 m^2 governmental buildings that are categorized in three groups: universities (1,9 mill. m^2), office buildings (0,9 mill. m^2), and private leases (1,2 mill. m^2), which are rented out by BYGST and later sub-rented to its tenants such as ministries, governmental agencies, police, courts etc. The agency is currently undergoing the change management process to transform its silo-based organisation into a data-driven knowledge organisation. Relating to that, BYGST has decided to implement IWMS and EMS to ensure standardisation of core building data and business processes across the entire organisation.

4.2. Postnord Denmark

Postnord Denmark (DK) provides postal services to households and businesses in Denmark. Postnord DK had 9.313 employees at the end of 2016. Due to decreasing postal demand in Denmark, Postnord DK has had several reorganisations and employment reductions over the past years. Consequently, the property portfolio has also been reduced from 650.000 m^2 (in 2012) to approx. 600.000 m^2 (in 2017), and the space optimisation process is still ongoing. All FM related tasks are outsourced to an external service provider, and Postnord DK only has one employee responsible for communication and coordination with external FM service provider. Postnord DK is a part of the Nordic postal consortium "Postnord" that also has branches in Finland, Norway and Sweden.

4.3. KMD

KMD is the largest IT company in Denmark and has more than 3.200 employees. KMD provides IT services primarily to Denmark's public organisations, but has also customers in the private sector, both domestically and in Sweden and Norway. KMD has departments in the four largest cities in Denmark and its building portfolio covers the total area of approx. 105.000 m^2. In 2016, KMD had a large reorganisation of the FM department and reduced the number of employees from 28 to 16. The new FM organisation is now divided in Hard and Soft service departments. The hard FM department is responsible for operation and maintenance of office and production (IT-server) buildings and handyman tasks. The soft FM department is responsible for cleaning, reception, canteen, travel arrangements and administration. The amount of FM service providers was also reduced from 78 (with and without service agreements) to 16 with service agreements. The new FM service providers are national and thus able to deliver service at all KMD locations. In relation to the recent FM reorganisation, it has been decided to implement IWMS and EMS to support the change process and strengthen the new, more centralised FM organisation.

4.4. Anglia Ruskin University

Anglia Ruskin University (ARU) is an educational institution in United Kingdom. The university has around 18.000 students and 1.800 staff members at three main campuses in UK: Chelmsford, Cambridge, and Peterborough. The university has 191 buildings covering 93.000 m^2 of academic floorspace and 26.000 m^2 of residential floorspace.

5. Findings

5.1. IT systems, their features, and user groups

For comparing IT systems used for managing EBP in selected organisations, an overview of the cross-analysis of previously described cases is shown in Table 2. The analysis reveals similarities and differences across different organisations when it comes to their usage of IT systems in relation to FM and EBP.

	BYGST (DK)	**Postnord Denmark (DK)**	**KMD (DK)**	**Anglia Ruskin University (UK)**
Organisation type	Governmental real estate agency	Public postal company	Private IT company	Educational institution
Portfolio size (m^2)	4.000.000	600.000	105.000	119.000
Main IT system(s)	EMS (IWMS*)	EMS	MS Excel BMS (EMS*)	BMS EMS CAFM
Features	Energy management Benchmarking	Energy management Benchmarking	Energy reporting Benchmarking	Energy management Indoor climate
KPIs	Consumption (hourly) Consumption vs. budget Benchmarking (m^2) Degree-day adjustment Emissions reporting	Consumption (hourly) Consumption vs. budget Benchmarking (m^2)	Consumption (monthly) Benchmarking (location, use type)	Consumption (½ hour) Emissions reporting Benchmarking (m^2, FTE, income)
User groups	Energy managers Facilities managers Other employees External users - Tenants	Facilities managers CSR dept.	Facilities managers CSR dept.	Facilities man. Sustainability eng. Environment man. CSR dept.

Table 2: Cross-analysis of cases.
**Ongoing implementation.*

The portfolio size in the selected cases ranges between 105.000 and 4.000.000 m^2, and the analysis shows that the organisations use different IT systems to manage their facilities and EBP. According to their features, the systems can be grouped in three main categories: simple systems (like Excel), single point systems (BMS and EMS), and complex systems (CAFM and IWMS).

Two organisations (BYGST and Postnord DK) use EMS for managing EBP, while two other organisations (KMD and Anglia Ruskin) use combination of several IT systems to manage EBP. BYGST is currently developing an interface between EMS and IWMS and plans also to use IWMS for strategic reporting of EBP. KMD has been using Microsoft Excel and combined it with BMS over several years to manage EBP, but the organisation is now in the process of implementing EMS. ARU uses BMS, EMS and CAFM to manage EBP on different organisational levels.

The identified IT systems are mainly used for energy management and benchmarking, with different degree of system functionality and data resolution across organisations. For example, KMD uses

Microsoft Excel and BMS for manual reporting and benchmarking of aggregated (monthly) energy consumption across building locations (four cities) and use type (office space, print centre, data centre)(interview, FM director).

Contrary to KMD, Postnord DK performs similar tasks by using EMS. The EMS solution at Postnord DK automatically provides high-resolution (hourly) consumption data, which is used for energy reporting and benchmarking across the building portfolio and the use type (e.g. office space, production line etc.).

BYGST also uses EMS for automatic monitoring of hourly energy consumption across its office buildings and to benchmark the actual energy consumption with expected energy consumption based on the last year's consumption. Moreover, the EMS at BYGST and Postnord DK is used for adjusting the heating consumption demand according to weather conditions (degree-day adjustments) and for calculating GHG emissions based on the actual consumption (interview, technical consultant).

ARU uses BMS, EMS and CAFM for monitoring hourly energy consumption and for GHG reporting. At ARU, the EMS is used as energy metering system for benchmarking building performance and for bill validation. The electricity and gas data are sent every ½ hour from BMS to EMS and the readings are presented in an energy dashboard tool. The water consumption is reported on higher level, i.e. with lower data resolution. The data resolution seems to have close ties with the financial value of each consumption type. The energy consumption (electricity and heating) at ARU was estimated to 2.2 million £/yr. while water consumption was estimated to 100.000 £/yr. According to the environmental manager, these financial costs are the main reason why the focus is on energy, and less on water consumption.

Several user groups can be linked with the identified systems. The main users of EMS are energy specialists such as energy managers, facilities managers, energy consultants and CSR departments that require insight into high-resolution data on building energy performance. EMS can also provide access to the end-users (e.g. tenants) through an add-on web-service solution, so they can monitor their individual energy consumption and compare it with the planned consumption. BMS is primarily used by the technicians and mechanical engineers to monitor HVAC's technical performance. Combined with EMS, IWMS can be used to consolidate energy data with other building-related data to create new KPIs and dashboards on building performance. These IWMS features can be used by the top management for strategic reporting on EBP. CAFM can also be used for strategic reporting on EBP, but depending on its configuration, CAFM might have limited cross-functionality features when compared with IWMS.

5.2. IT systems and environmental building performance

The more comprehensive analysis of IT systems and their features on different environmental categories is presented in

Table 3. All four organisations use IT systems to report and benchmark energy, water and GHG emissions on different levels. The organisations also collect data on waste from different external sources for reporting purposes, but these data are not stored in the studied systems. KMD and ARU, both ISO 14001 certified, also collect data on reuse potentials for some specific topics like hazardous materials and waste recycling. Indoor environmental quality (IEQ) is partially covered through BMS, while the remaining environmental categories are not managed through the studied IT systems.

	BYGST	**KMD**	**Postnord Denmark**	**Anglia Ruskin University**
Organisation type	Governmental real estate agency	Private IT company	Public postal company	Educational institution
Portfolio size (m^2)	4.000.000	105.000	600.000	119.000
Main IT system(s) for EBP	EMS IWMS*	Excel BMS EMS*	EMS	BMS EMS CAFM
Energy management	YES	YES	YES	YES
Water management	YES	YES	YES	YES
Emissions	YES	YES	YES	YES
Waste management	(YES)	(YES)	(YES)	(YES)
Space management	NO	NO	NO	NO
Building materials	NO	NO	NO	NO
Indoor environmental quality**	(YES - BMS)	(YES - BMS)	(YES - BMS)	(YES - BMS)
Reuse potential	NO	(YES)	NO	(YES)

Table 3: Environmental categories covered by the IT systems.
**Ongoing implementation. **IEQ category: Some indicators are monitored and reported on through BMS.*

When it comes to energy and water management, all four organisations use IT systems to report and benchmark electricity, heating and water consumption. In Denmark, EMS seems to be the preferred IT system for this purpose. The reasons might be the system's connectivity with the consumption meters and the ability to collect the consumption data directly from the utility companies. For example, BYGST and Postnord DK automatically receive hourly data on electricity, heating and water consumption to EMS directly from their consumption meters. Moreover, EMS also includes additional features on energy management such as water flow, heating efficiency, volume etc., but these features depend on the technical characteristics of each consumption meter. As observed at BYGST, managing EBP through IT systems can be further supported with IWMS, where consumption data from EMS is combined with building-related data to create new insights on energy management and real estate management.

The organisations without EMS seem to use BMS and combine it with other IT systems to manage EBP. KMD has been using Excel ten years for energy reporting and benchmarking, demonstrating that also simple IT systems can be used for energy management to a certain level. KMD collected the consumption data in Excel partly through remote readings in BMS, and mostly through manual consumption readings on all locations (interview, FM director). However, this manual data collection process included the risk of consumption misreading and typing errors in Excel, since the system itself did not contain any data validation features. Due to the recent FM reorganisation and reduced number of FM employees, KMD has now decided to automatize data collection process and ensure data validity by implementing EMS.

Anglia Ruskin University uses BMS and EMS for energy management and combines the data with CAFM to provide deeper insights on EBP. In this case, BMS is used by a sustainability engineer for monitoring HVAC installations and their energy performance. EMS is used by an environmental manager. However, the BMS system lacks important notification features on inadequate indoor temperature, which often leads to reactive maintenance rather than preventive tasks. The BMS is also rarely maintained due to few human resources, leading to reduced system functionality and questioning data validity (interview, sustainability engineer).

Besides energy and water management, IT systems like EMS, CAFM and IWMS can be used to calculate and report GHG emissions. The calculated emissions are typically based on the actual energy consumption, which later is converted into GHG emissions through the standardisation factors included in the software or defined by the users. The reporting format is typically CO_2 or CO_{2e} in kilograms.

An in-depth study of the identified systems showed that they contain additional functionalities related to EBP, but that these are not used in practice. For example, EMS can offer waste management, but none of the studied organisations was using this functionality. IWMS and CAFM include space management features that can visualise how the building area is being utilised, but also this functionality was not in use in any of the studied organisations. On the other hand, the study disclosed that data and functionalities related to building materials, their properties and maintenance, as well as the reuse potential of building components were missing in the examined IT systems.

Regarding indoor environmental quality, some indicators related to energy like indoor temperature, air quality and relative humidity can be monitored and reported through BMS. It is however different, how the studied organisations manage IEQ in practice, since their building portfolios contain many different buildings with varying age, use type and technical conditions (e.g. natural or mechanical ventilation), which leads to a disperse picture on IEQ performance. The systems like EMS, CAFM and IWMS do not seem to offer deeper insight into IEQ but appear to be solely focusing on reporting and benchmarking energy consumption, while BMS covers the technical aspects of HVAC installations and hereby partially covers IEQ indicators.

6. Discussion

The IT systems used for managing EBP range from simple systems like MS Excel, single point systems like BMS and EMS, till more complex, cross-functional systems like CAFM and IWMS. The system type used in different organisations seems to be determined by the benefits each IT system can bring to an organisation and the organisational needs on environmental performance reporting. All studied organisations use IT systems to monitor and benchmark energy and water consumption, categories that beside environmental impacts also have large impacts on operational costs and the financial bottom line. However, the organisational approach to energy and water management varies greatly. As illustrated earlier, some organisations collect the data manually and monitor energy consumption on a monthly basis, while other organisations require automated, detailed, hourly reporting, leading to different possibilities in data analytics. Having access to high-resolution (hourly) consumption data can visualise not only energy consumption, but for example also show how the consumption is distributed between working hours, non-working hours and during weekends, and enable new benchmarking possibilities. Moreover, the automatic data processing systems like EMS should be preferred, since they can release valuable human resources and reduce the risk of misreading and typing errors when using manual readings.

The cross-case analysis indicates two general IT models for managing EBP: one based on EMS and its add-ons, other on BMS and its add-on solutions. The main differences between the two models are presented in Table 4.

	BMS	**EMS**
System type	Single point	Single point
Data source(s)	Technical installations (HVAC) Sensors	Consumption meters
Data capture method	Automatic Manual	Automatic
Data processing	Mostly manual	Automatic
Key features	Indoor comfort (temperature) Air quality Ventilation frequency	Electricity consumption Heating consumption Water consumption
Typical users	Technicians Facilities managers	Energy managers Facilities managers Utility companies End-users (through web-tools)

Table 4: The BMS and EMS models as observed through the cases.

In Denmark, the EMS model seems to be the dominating model for managing EBP. EMS is used for automatic collecting of hourly consumption data and can be used as a stand-alone solution or combined with other IT systems. The BMS model was observed at ARU, and it showed similarities with the system configuration used in one Danish case (KMD – now implementing EMS). The BMS model relies mainly on the performance data from HVAC, which later are manually processed, either in a specific BMS software or in other IT systems, like Excel or even EMS.

Both BMS and EMS model focus on energy performance through different approach. While EMS model is based on collecting the consumption data from consumption meters and used for automated monitoring of energy consumption across building portfolio, BMS model is more technical, focuses on specific HVAC installations, and has therefore more measuring points within each building compared to EMS model.

The findings within this research indicate transition towards EMS models and more automated data collection. However, it must be pointed out that the BMS model should not be perceived as an opponent to EMS model, but more as an important supplementary model. The BMS model contains valuable data on indoor climate and building's technical performance, the data which are not included in the EMS model, but are very important for users' comfort and productivity, as well as for EBP.

When using the IT, the data source and data harvesting are important parameters. To collect consumption data in EMS, the utility company must be willing to provide the data into the system, even though the data concerns your own facilities. This raises several questions concerning data ownership (Who owns the data?), data management (How much data can utility company provide? Which data: only consumption, or also other measuring points?), data accessibility (Who should have access to your data?), exchange standards (Data format between utility company and EMS) etc., which not only relates to building owners, users/tenants and FM organisations, but also involves other external stakeholders like software developers, utility companies and legislators.

Another important subject regarding data collection in EMS is the technical aspect of consumption meters. The consumption data are delivered to EMS through remote readings. It means that the consumption meters must be digital and able to support remote readings for delivering data to EMS. However, the picture is very diversified when it comes to meter maturity of different consumption types. In Denmark, the electricity meters are most matured and support high-resolution data reporting (nowadays down to 5 minutes intervals), and there is a national data hub in which all electricity consumption data are stored. The utility companies provide data to the data hub, and the personal consumption data can be accessed through web access. The heating meters are also very mature, but not all heating suppliers are currently able to provide hourly data, and there is no national heating data hub. Water consumption data are most difficult to collect as there are still many manual meters, meaning that the water consumption is not as easy to monitor and benchmark as electricity and heating consumption. This meter/data issue was recently also highlighted by BYGST showing that 95% of electricity, 65% of heating, and only 35% of water consumption in their office buildings was automatically reported to EMS (Bygningsstyrelsen, 2017). The digitisation of consumption meters is still ongoing, so it is the matter of time until more consumption data can automatically be collected and managed in EMS.

None of the four cases included examples of attempts to measure the success of IT implementation in economic terms. However, in the IT implementation at BYGST, a benefits realisation framework was applied. The benefit realisation diagram for energy management at BYGST is shown in Anonymous (2018).

7. Conclusion

Environmental building performance can be managed through three types of IT systems: simple systems, single point systems, and complex systems. There is a great variance how these IT systems are used for managing EBP in practice, and to which extent they cover different environmental categories.

There are two dominating models for managing EBP through IT systems: EMS and BMS. The two models do not necessarily exclude each other and can be used supplementary. The EMS model appears to be the leading model for managing EBP in Denmark. It focuses on monitoring and benchmarking energy and water consumption and can also be used for waste management. The key benefit of EMS model is that it automatically collects consumption data through remote meter readings.

Companies not using EMS can use BMS and combine it with other systems to manage EBP. The BMS model requires more human resources since the data management is less automated compared to EMS, including higher risk of incorrect consumption data. On the other hand, BMS provides important data on indoor environmental quality, a feature that EMS lacks, and the BMS model should therefore be considered as a supplement to EMS.

The IT systems are mostly used for energy and water management, and for reporting GHG emissions. Some IT systems offer additional features related to EBP like waste management and space management, but these features were not in use in this study. On the other hand, IT systems lack features on building materials and reuse potential. The management of indoor environmental quality is partially supported through BMS, but rarely linked with other environmental categories. Deeper interaction of BMS with EMS, combined with interfacing with workflow systems like CAFM and IWMS might improve management of environmental building performance and provide more comprehensive picture of environmental sustainability within building portfolio.

This research mainly relates to Danish FM context and IT systems provided or related to the IT company KMD. As such, the results might be biased or limited, and there is therefore need for further research within this field. The authors suggest research on how FM organisations outside of Denmark use IT systems for managing EBP, what their organisational drivers and needs are, as well as determining which benefits IT systems bring to different stakeholders in relation to environmental sustainability. Moreover, there is also a need for comparative studies of organisations using BMS and EMS, to determine in which way these systems support EBP and how they can be combined.

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PAPER 6

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Environmental performance assessment of the use stage of buildings using dynamic high-resolution energy consumption and data on grid composition

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ABSTRACT

During the use stage of buildings, their consumption of electricity has proved to influence considerably their environmental performance. The impacts associated with using electricity are directly related to the electricity grid that delivers the power and hence are also closely associated with the impacts induced by the production of each kWh delivered to the grid. Life cycle assessment (LCA) usually does not account for the variations in the energy sources that supply an electricity grid every day, month and year. This study addresses the dynamic nature of electricity grids and accounts for the source variations in electricity production using electricity grid data at high temporal resolutions. The study compares inventory data on electricity grid composition at hourly, daily and monthly resolutions with the conventional yearly average grid compositions from the ecoinvent database. The high-resolution electricity grid inventory data are subsequently paired with data sets for electricity consumption by buildings with matching resolutions in order to quantify the differences in the environmental performance of buildings resulting from the application of temporally high-resolution grid data. Finally, environmental building performance (EBP) calculated using high-resolution grids is compared to EBPs generated from conventional data resolutions. The results indicate that the contribution to global warming potential is closely related to the data resolution of the grid composition and that the EBP may be overestimated by up to a factor of two when compared with conventional grid inventory data with yearly (i.e. low) data resolutions.

1. Introduction

1.1. Dependence on electricity

Electricity is an essential part of modern society. Our dependence on electricity has its origin in the industrialization of the western world, where the large-scale introduction of electricity accelerated global industrialization by providing “easily available, cheap, and reliable energy from non-renewable fossil fuels, such as coal, oil, and natural gas” [1], [2]. Fossil fuels are still a major component of the global energy mix, with larger shares in emerging and developing economies.

The energy crisis of 1973 left Denmark and other Nordic countries in a situation that forced them to rethink their national energy supplies not only by moving away from being solely reliant upon fossil fuels, but also by reducing their dependence on the energy resources of foreign countries. This resulted in an ambition to develop renewable domestic energy sources suitable for the political and geographical situation of each Nordic country. In Denmark this led to the large-scale construction of infrastructure to harness wind power, while Norway decided in favour of hydro-power, and Sweden and Finland opted for biomass from their vast forests, which they combined with nuclear power. Today all these countries still import energy, but at a much lower scale than in the 1970s, and mainly from neighbouring countries.

Current opinion globally is that it is not enough for a country to meet its total energy demand solely by replacing non-renewable energy sources with renewable ones [2]. It is also necessary to reduce global energy consumption drastically, thus countering the misconception that humanity's potential to produce is limitless [3].

In Denmark, total energy consumption was 744 PJ in 2017, of which electricity consumption represented 122.5 PJ or around 16.5% [4]. Fig. 1 shows the distribution of total electricity consumption in seven selected sectors in Denmark. The office buildings assessed in this study fall under the category “public service” buildings, which in 2017 consumed 8% of Denmark's total electricity consumption.

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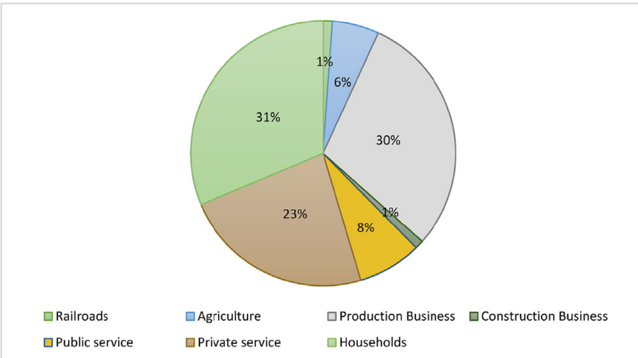

Fig. 1. Distribution of electricity consumption in Denmark in 2017.

1.2. EBP optimization through LCA

Life-cycle assessment (LCA) is often used to gain understanding of the environmental impacts associated with the manufacture or maintenance of a given service, product or system. It is common to perform an LCA on a building to assess the impacts of all the stages in the life-cycle of a building [5], [6]. According to EN 15978 [7], the building life-cycle covers four stages: product, construction, use and end of life. The use stage of a building is its operational and maintenance period and includes operational energy consumption.

In the total life-time of conventional buildings, it is the use stage that has most of the negative environmental impacts [3]. In EBP assessments of various building types (residential, commercial, agricultural etc.), the impacts induced during the use stage generally play a predominant role. Earlier research showed that the use stage may represent as much as 90% of the aggregated impacts of buildings [5], [8].

In the use stage, the main contributor to the overall environmental impact is energy consumption [9]. Since energy consumption plays such a crucial role in the EBP, it is clearly essential that quantifying the environmental impacts induced by energy consumption is as representative as possible.

Currently, when it comes to the EBP of buildings, the usual method is to apply a static power grid that does not vary throughout the lifetime of the modelled building system, combined with yearly estimates of annual average power consumption [10]. The combination of these two parameters allows the environmental impacts resulting from the building's energy consumption to be quantified [11].

Given how important energy consumption is for the EBP, and as Sohn et al. have demonstrated [12], using only static power grids and relying on yearly averages may not be the correct way to present the actual performance of the building in question. However, the neglect of temporal differentiation is one of the most significant drawbacks of LCA, one that has been addressed several times in published research on it [13–15]. Furthermore, Anand and Amor [16] argue that some of the gaps in the LCAs of buildings can be covered by incorporating more dynamic aspects for tracking the potential changes over a long period. Also, Roux et al. [17] argue that current LCA practice based on a documented reference year should be replaced by the temporal variability of electricity production within a year. For example, they found that the discrepancy between the annual and hourly impact results could be over 40% for some indicators. This article therefore examines the LCA application of high-resolution dynamic energy data in office buildings, taking into consideration parameters like temporal variations in the composition of the power grid, as well as the building's location, age and size.

The aim of the present article is thus to quantify the importance of accounting for the variations in electricity production throughout the year. This task is accomplished by quantifying the environmental impacts induced by electricity consumption in office buildings with an hourly data resolution to account for changes in consumption and grid composition simultaneously. The purpose is to quantify the variations in the impacts per kWh consumed throughout the year and to combine these time-dependent impacts with actual electricity consumption data in order to obtain the most accurate EBP assessment of the building's use stage as possible [18].

The energy grid data and energy consumption data for buildings are compared at different resolution scales in order to analyse the differences in the EBPs so that recommendations can be made as to which method is most pertinent.

Lastly, the high-resolution energy calculations are compared with a standard, static system assessment approach, where, in respect of energy consumption, the EBPs are calculated using the standard method, and the degree to which these results differ is quantified.

1.3. Dynamic LCA

As a concept, dynamic modelling in LCAs has emerged over the past few years, the intention being to counteract some of the shortcomings inherent in traditional, static LCAs. Where traditional LCA practices are more rigid in their structure, dynamic system models and/or system inventories allow for the inclusion of parameters that change throughout the temporal scope of the LCA, thus reflecting more accurately the real-life circumstances of the system being assessed [19].

Dynamic system modelling often includes temporal variations in unit processes, and in some cases this consideration leads to results that differ from their static counterparts [12], [14].

Dynamic LCAs differ from conventional ones through the inclusion of temporal and spatial variations in the system modelling [20]: just as the temporal considerations have major implications for the accuracy and representativeness of the LCA as a whole, so can spatial variations influence the results of an LCA and thus the conclusions drawn from it. With regard to building LCAs, a key aspect of the overarching results is occupant behaviour, which, over the course of a buildings' long life-span, has great potential to affect the EBP [15], [21].

Naturally there are limitations to the application of dynamic modelling practices in LCAs. While the temporal considerations potentially yield significantly greater accuracy in the impact modelling, they also necessitate vast amounts of data. In most cases the data required to perform the LCAs at the highest resolutions (i.e. temporally and spatially dynamic) are not available, limiting their representativeness [20]. In scenarios in which the data necessary to perform dynamic LCAs are available, these data can relieve the uncertainties from the static product system models that might otherwise arise.

Even though dynamic LCA practices have already been proved to yield informative results, the full extent of their implementation is not yet known, and the methods are still relatively new. The application of dynamic frameworks has the potential for far-reaching implications in the field of LCA, and such frameworks are continually being developed further. Recent studies have evaluated the applications of dynamic characterization, showing that the different impact categories do not react identically to temporal dynamic frameworks [22]. In the sensitivity analysis presented by Shimako et al. [22], it is shown that, for both climate- and toxicity-related impacts, the temporal considerations influence the results when compared to static systems. Furthermore, Shimako et al. [22] show that the time increment (i.e. the temporal resolution) one choses has the greatest effects on the toxicity-related impacts, while the climate change-related impacts are not affected by the temporal resolution. This observation is assumed to be related to the time scale of the related impacts. That is, toxicity-related impacts have a maximum time-scale of months or a few years, while climate change-related impacts have time scales of decades or even several centuries, depending on the method of characterization.

As shown above, the implementation of dynamic LCAs has proved to be of major significance for projects where such an approach to assessment is feasible data-wise. Applying a dynamic framework therefore has the potential to influence the final results of an LCA significantly. However, the full implications of the approach are as yet unknown, and the practices are continually being expanded upon.

1.4. Electricity grids

When considering temporal variations within the LCA framework, the main objective is to divide the lifetime of the system into (smaller) time steps, for which, for example, the materials and energy supplied can also be divided. When assessing the energy consumption of a building, this approach provides a more detailed impact assessment framework and is an obvious improvement over conventional static system models, due simply to the much finer data resolutions and hence the number of variations that can be taken into consideration. While it is important to account for the timeframe of the energy consumption, it is potentially even more important to account for the variations in electricity grid composition during the same period [23], [24]. Thus, when constructing an inventory for, for example, energy consumption, it is no longer “just” a question of quantifying that consumption, but also of resolving it over time and determining *when* the energy is consumed, thereby adding an additional dimension to the inventory analysis. Depending on the national context and timeframe in question, the composition of the electricity grid has the potential to fluctuate considerably, and the environmental impacts caused by its production can change in an unsystematic manner, meaning that the impacts per unit of energy consumed also may change in an unsystematic manner [25], [26].

A national electricity grid is a complex infrastructure, with numerous processes and components to consider when assessing the environmental impacts induced by electricity production. The major factors to consider are the extraction of materials for purposes of production, the emissions generated by using these materials, the construction and maintenance of grid infrastructure, and the losses caused by transmission and transformation [27]. All of these factors must be taken into account when making recommendations for changes to the grid. Given also the scale of the system and the desire for affordable energy, it can be difficult to find the best solution [28].

Denmark is in a unique situation when it comes to global ambitions for the future of renewable energy, as these have also been Denmark's ambitions for many years, and as a result much of the required infrastructure is already in place. However, the Danish power grid still relies on non-renewable sources, as well as imports of energy from countries that rely heavily on non-renewable energy sources. Nonetheless, future plans for a Danish power grid seek to make the grid completely independent of international sources of power and 100% reliant on renewable energy. The key component of the 2050 renewable-energy grid plan is the flexibility of the grid [2]. The goal is to shape the infrastructure so as to accommodate short- and long-term changes in renewable energy sources in order to utilize the energy being produced fully, combined with an overall decrease in energy demand.

As such, granting the use stage and hence energy consumption a more prominent role in LCAs of building is only logical, and it has the potential to play a major part in the development of the dynamic framework of building LCAs in the future.

1.5. Dynamic high-resolution data

Dynamic high-resolution data are data used in combinations of dynamic modelling practices, which divide traditional data into many smaller components, allowing for an increase in the number of data points available to portray the system to a much higher degree of detail and to identify tendencies that would not be visible otherwise.

With respect to this study, high-resolution data are included by dividing the year into months, days and hours, instead of using just one yearly average representing a single data point aggregating 8760 hourly data points into one single data point or aggregating 365 daily data points into one single data point. Depending on the approach to aggregation, it is assumed that a simplification reducing the data resolution by three to four orders of magnitude can be regarded as representative.

Coupling dynamic inventory analysis with dynamic system modelling, as presented here, has the potential to increase the representativeness of an LCA substantially and thus to reduce the uncertainties that are otherwise inherent in similar assessments that do not account for changes throughout the year. Especially in relation to assessments of the absolute EBP, as presented by, for example, Brejnrod et al. [3], the representativeness of both the inventory and the system model will play an important role in achieving the overall validity of the results obtained.

2. Methods

2.1. Data collection

The study is based on high-resolution inventory data sets on the energy source composition of Denmark's national electricity grid and building-specific electricity consumption data on eighteen office buildings located in eastern and western Denmark. Both data sets have an hourly resolution covering the whole of 2017.

National electricity grid data are provided by Energinet, Denmark's national transmission system operator for electricity and natural gas [25]. These data are supplemented by further data on energy production in Denmark from the Danish Energy Agency [29]. The purpose of drawing supplementary data from the Danish Energy Agency was to increase the resolution of the data for both local and central power production by using the data to enable both forms of power production to be distinguished according to their basic sources (biomass, biogas, natural gas, etc.).

The Danish Building and Property Agency (Bygningsstyrelsen or BYGST) provided specific electricity consumption data for eighteen state-owned office buildings, matching the data format and resolution of the electricity grid data. The eighteen office buildings selected for the study are equally distributed between eastern and western Denmark, with nine in each part of the country. More details on all eighteen buildings are provided in Table 6 of the supporting information (SI). One building (W2) lacked hourly and daily data resolutions and was therefore left out of the subsequent analysis.

The buildings have been anonymized and are denoted by a letter and a number only. This is due to the sensitive nature of data on electricity consumption, which are protected by Danish law. The consumption data were provided through a special legal agreement with BYGST.

2.2. Regionalization of the energy data

The data from Energinet are intrinsically divided into eastern and western Denmark, the dividing line being the Great Belt, that is, the sea between the islands of Zealand and Funen. The reason for this regional split is the practice of transferring energy between eastern and western Denmark, especially from west to east.

While overall imports of fossil fuels for electricity production have declined steadily since the 1970s, both eastern and western Denmark still import a considerable proportion of the energy they consume. The east primarily imports energy from the other Nordic countries (and to some degree from western Denmark), the west mainly from neighbours on the European continent, especially Germany.

2.3. Reference impact values (openLCA & ecoinvent 3.3)

Data on the national electricity grid obtained from Energinet and the Danish Energy Agency divides the energy mixture into the following energy sources: oil, coal, waste, solar, offshore wind, onshore wind, natural gas, biomass, biogas, exchange with Nordic countries and exchange with the European continent.

Using the openLCA software [30] and the ecoinvent 3.3 inventory database [31] in combination with the characterization model and impact categories from ReCiPe ver. 1.11 – hierarchical perspective [32], the reference impacts for the production of 1 kWh of each energy source were calculated, both for midpoint impact potentials and endpoint scores using ReCiPe (H).

The total impacts per kWh were calculated using the energy source-specific unit impacts (i.e. source-specific impact per kWh produced) for each of the energy sources in the Danish grid. Combining the energy source-specific unit impacts with the determined composition of the energy grid, the impact for each hour of the calendar year 2017 for each impact category was calculated by multiplying the relative source contributions per hour with the corresponding energy source-specific unit impacts.

In addition, the loss in energy due to either transformation or transmission was determined from the differences in gross and net electricity production. These energy source-specific loss factors were later multiplied by the electricity consumption of the buildings to improve the precision of the actual power grid data.

The same method was used to determine the average impact potentials of every kWh per day and per month. This procedure would later facilitate the quantification of the differences in the overall EBPs when using varying data resolution in the quantification of the energy grid and energy consumption combined impacts.

The energy consumption-induced impacts at the midpoint and endpoint levels of the individual buildings were calculated hourly, daily and monthly using the existing national-grid process for Denmark in the ecoinvent database in combination with the measurements of energy consumption. The purpose of this calculation was to establish data resolution-specific reference points allowing the building-specific impact changes to be quantified by relying on conventional ecoinvent inventory data or actual high-resolution energy grid/consumption data. The goal of comparing the two different ways of quantifying the EBP is not only to evaluate whether higher energy grid/consumption data resolution can have a significant influence on the overarching EBP results, but also to determine which level of data resolution is most appropriate.

3. Results

3.1. Energy grid results

Fig. 2 presents the results obtained from the initial calculations of the reference impact for global warming potential (GWP) of the various energy sources for Denmark's energy production processes. The figure shows the GWP induced by the production of one kWh for each energy source. The total contributions from each energy source within the various categories are presented in Table 1 of Appendix SI-C. These energy source-specific unit reference impacts constitute the foundation for later calculations of the impact potentials of every kWh produced per hour, per day and per month.

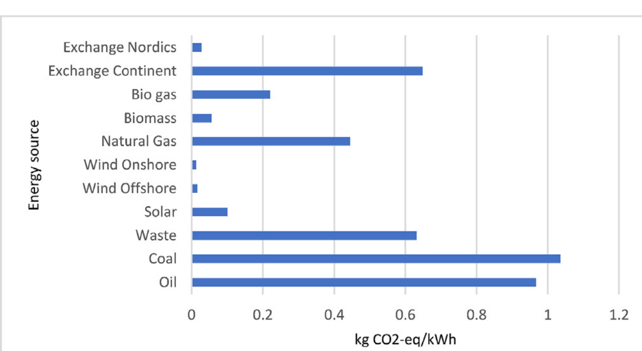

Fig. 2. Source-specific GWP/kWh [kg CO2-eq/kWh] showing the contribution to the GWP for each of the energy sources comprising the Danish electricity grid as calculated from openLCA.

Table 1
Average monthly deviations of all midpoint impacts from the yearly average for western and eastern Denmark. See Table 2, Appendix SI-C, for further information.

Average deviation in impact categories	West	East
January	111.8%	109.3%
February	116.7%	114.6%
March	114.8%	127.8%
April	104.8%	114.6%
May	98.4%	86.1%
June	70.8%	89.4%
July	66.4%	81.2%
August	102.2%	78.9%
September	102.8%	74.5%
October	101.6%	109.6%
November	102.5%	100.8%
December	107.1%	113.3%

Fig. 3 presents the calculated GWP impacts per kWh based on the hourly grid resolution in order to reflect the monthly average variation throughout the year. The yearly averages were calculated from the electricity grid impact results, and the deviations from the averages are displayed in percentages.

Fig. 3 shows a significant difference in the GWP per kWh for western and eastern Denmark, depending on the month in which electricity production takes place. The corresponding data, that is, the endpoint results, are provided in section 3.1 of the SI. The scores for the remaining impact categories can also be found in Appendix SI-C, showing the substantial changes that occur on a monthly basis. For instance, in western Denmark, agricultural land occupation scores are 156.3% of the yearly average in January, but only 384% in June for the same amount of electricity produced. The eastern grid shows the same trends. Table 1 summarizes the results of these impact score variations presented as monthly average deviations from the yearly average. Table 1 further shows that in western Denmark the deviation in impact categories for January is 11.8% higher than the yearly average, while equivalent production in July on average induces 33.6% less impacts.

The general tendency in western Denmark is that any power produced from May to July will have a lower impact compared to the remaining months when calculating the average across all categories. This is caused by variations in the composition of the electrical grid between these and the remaining months. For the eastern Danish grid, this also includes August and September. However, when looking at a specific single-impact category, the opposite may be true in some cases. For instance, electricity produced during these five months in the west

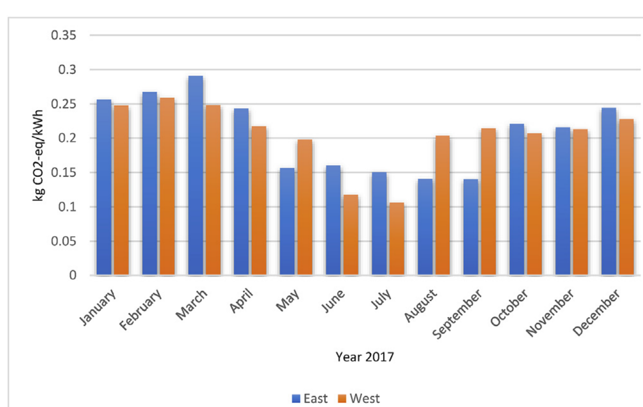

Fig. 3. Monthly average GWP/kWh for eastern and western Denmark.

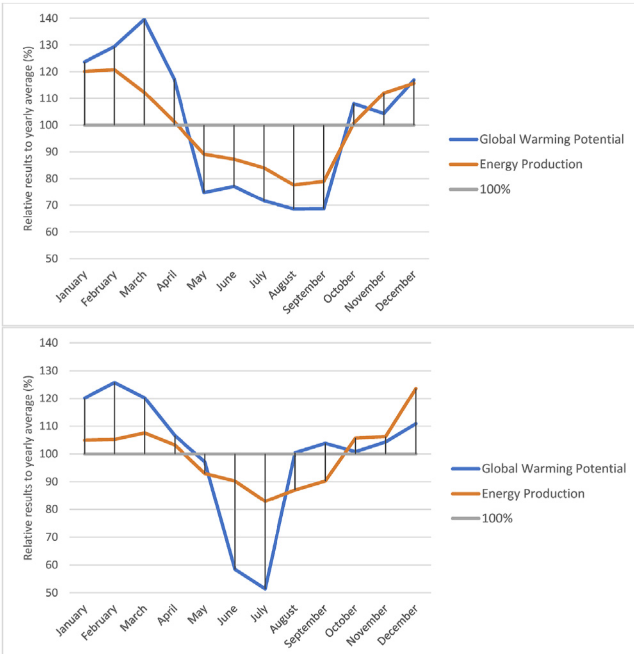

Fig. 4. Deviation from average monthly electricity production and global warming potential per kWh. 4A: eastern Denmark (upper graph); 4B: western Denmark (lower graph).

will have a larger impact in terms of water depletion than in other months due to the water depletion related to solar power production, as highlighted in Table 2 of Appendix SI-C. Table 1 in the SI shows the same results for the eastern grid.

Fig. 4A and B present the monthly impact deviation from the yearly averages for electricity production and the associated global warming potential in western and eastern Denmark calculated on the basis of an hourly grid-composition data set. The figures show that the months with lower impacts per kWh also have lower overall energy production, with the exceptions of August and September in western Denmark. August and September have lower electricity production than the yearly average, while also inducing greater impacts per kWh than the yearly average. In eastern Denmark the same pattern is not observed, and all the months with lower electricity production induce fewer impacts per kWh electricity produced. The monthly deviations for the remaining impact categories are given in the Appendix to the SI.

Apart from August and September, the general trend in the west follows an increase in induced impact per kWh in months when the demand for electricity is high. This is caused by the current limitations in Denmark's capacity to produce energy from sources that have less impact.

The production of electricity from renewables in Denmark – mainly wind and solar power – currently has three main disadvantages. First, the amount of energy produced by these sources is highly dependent on weather conditions: if no wind is blowing, or if it is cloudy, production is limited. Secondly, we do not yet have the ability to meet the total energy demand during periods of peak demand solely from renewable sources and are therefore dependent on secondary (adjustable) energy sources at these times. Lastly, we have not yet developed efficient ways to store excess energy harnessed from renewable sources, meaning that any such over-production of electricity is wasted when produced at times of low demand. These factors mean that renewable energy sources are not entirely reliable in their current state.

Fig. 5 shows the contribution of each electricity source to the national production of electricity for the months of June and December for both eastern and western Denmark. In all four cases the local level of power production serves as a baseline that does not vary greatly on a daily basis, while other sources, such as wind, displayed in green and purple, fluctuate notably. For times when wind production is low, electricity production is supplemented primarily by imports of energy from other countries or through central power plants.

The difference in electricity produced by central power plants and electric boilers respectively is great and is due primarily to the burning of coal and biomass. Reliance on these sources is on average 778% (central power plants) and 406% (electric boilers) higher in December. The substantial disparity between these two months is caused by the combination of higher energy demand during the winter months and the lower potential for renewable energy during this season.

The effect is a substantial difference in the contributions from individual sources, depending on which time of the year the energy is produced, and leading to an equally substantial difference in the environmental impacts of its production.

Fig. 6 charts the development of the Danish electricity grid over the last five years, showing the yearly averages of the contributions of each of the nine main sources comprising the grid. The highlighted data cover only the production of electricity for domestic use and do not take any exported electricity into account.

Over the years, the Danish power grid has evolved significantly and caused considerable fluctuations in respect of some of its sources. It should also be noted that 2012 is the reference year for the ecoinvent data, and 2017 the reference year for the electricity consumption data and grid compositions used in this study.

From 2012 to 2017 reliance on local power plants decreased from 9.18% to 7.12%, while the central power plants, which in 2012 supplied 23.52% of total electricity production, only accounted for 15.72% of the electricity produced in 2017. Parallel to the decline in the sources mentioned above, there has been a significant increase in the capacity of wind and solar power. Offshore wind power increased from 6% to 8.5% along with onshore power, which increased from 11.85% to 15.86%. Meanwhile, solar power has increased from zero in 2012 to 1.3% today.

3.2. Building-specific results

The available building-specific energy consumption data give hourly electricity consumption figures for each of the buildings in the study.

Two buildings deviate significantly from the rest. Building W2 only provides aggregated monthly electricity consumption data, thus ruling out hourly comparisons. The second building, W4, is equipped with solar panels that reduce the demand for electricity from the grid during the summer months. As a result building W2 was excluded from the study, while W4 remains included, but with its own electricity production excluded from the calculations, thus utilizing only the data for the electricity delivered to it from the outside.

Fig. 7 reveals that the larger buildings consume more energy, while the smallest buildings have the highest electricity consumption per m^2. When sorting by age, there is no clear trend between building age and total electricity consumption and consumption per m^2 except that the newer buildings have generally higher level of consumption, meaning that the area of a given building is a more significant factor in this sort of comparison.

As also shown in Fig. 7, the total electricity use of the western buildings is quite similar to that of the eastern buildings and differs only by 2% on average, while the consumption/m^2 on average is 33.4% higher on an annual basis for the buildings in western Denmark.

3.3. Results of combining energy consumption and grid composition

After collecting the data on energy grids and building-specific electricity consumption, the data are combined to determine the actual environmental impact induced by electricity consumption in seventeen office buildings. The analysis has two targets: to compare the results for

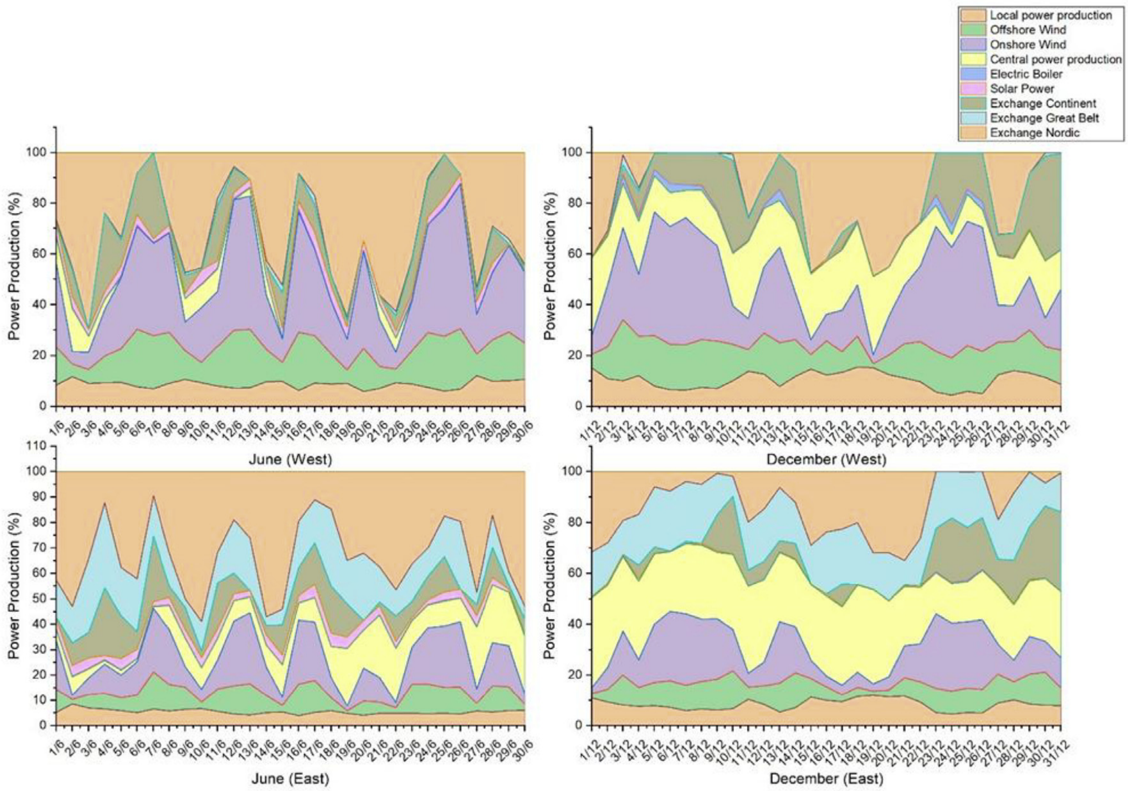

Fig. 5. Distribution of electricity produced by source for June and December. 5A: June (west); 5B: December (west); 5C: June (east); 5D: December (east).

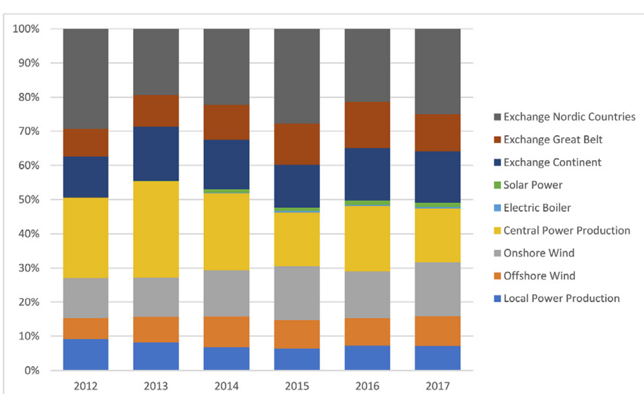

Fig. 6. Yearly development of electricity grid from 2012 to 2017, Denmark as a whole.

the seventeen buildings obtained using the high-resolution data; and to quantify any application differences between these results and those using conventional averaged data found in ecoinvent.

The comparison is made using both midpoint impact potentials and endpoint scores. Five midpoint categories are highlighted in this article: marine eutrophication, terrestrial acidification, photochemical oxidant formation, climate change and ozone depletion. All midpoint impact potentials are presented in Appendix SI-A. The final comparison between the different data resolutions includes all midpoint and endpoint categories, as presented in section 4.4.3 of the SI.

3.3.1. Hourly data resolutions

The hourly data for power grid composition and electricity consumption have the highest resolutions and as such are considered the most accurate. However, assessments at this data resolution require significantly more data than the daily or monthly systems. Figs. 6–8 in section 4.1 of the SI give the hourly average distributions of both electricity consumption and impact potentials per kWh. Figs. 6–8 in section 4.1 also show the progression of electricity consumption and production throughout a day based on the total yearly data.

Data with hourly resolutions facilitate the inclusion of the small-scale deviations that occur over a day, such as the significant grid changes in terms of energy sources from day to night, or variations in energy demand between working and non-working hours.

In general, electricity consumption in Denmark is significantly higher during October, November and January, which are also the months with the highest impact potentials per kWh.

Table 2 shows the total midpoint impact potentials for the chosen impact categories. The midpoint impact potentials are on average 37% higher for buildings located in western Denmark, while the endpoint scores for these buildings have on average 33% higher impact potentials when compared with buildings in eastern Denmark. The buildings in western Denmark have generally higher impact potentials per m^2, as shown in section 3.2 of the SI.

3.3.2. Daily data resolutions

By using daily data resolutions, some insights are lost by disregarding hourly variations in the energy grid throughout the day and instead assuming every hour of the day to have a uniform grid composition. On the other hand, the daily data resolutions account for the variance between weekdays, which is significant for office buildings, since the difference between weekdays and weekends is considerable. This is because the electricity consumed over the weekend is mainly used for "background" systems, and the amount consumed is hence lower than on weekdays.

The consumption data show substantial falls in energy demand on every weekend or holiday. The average daily energy demand (i.e. baseline) during weekends or holidays is about a third of the average of working days, the weekday variations being highlighted in the daily resolution section 4.2 of the SI. The total average daily deviations in

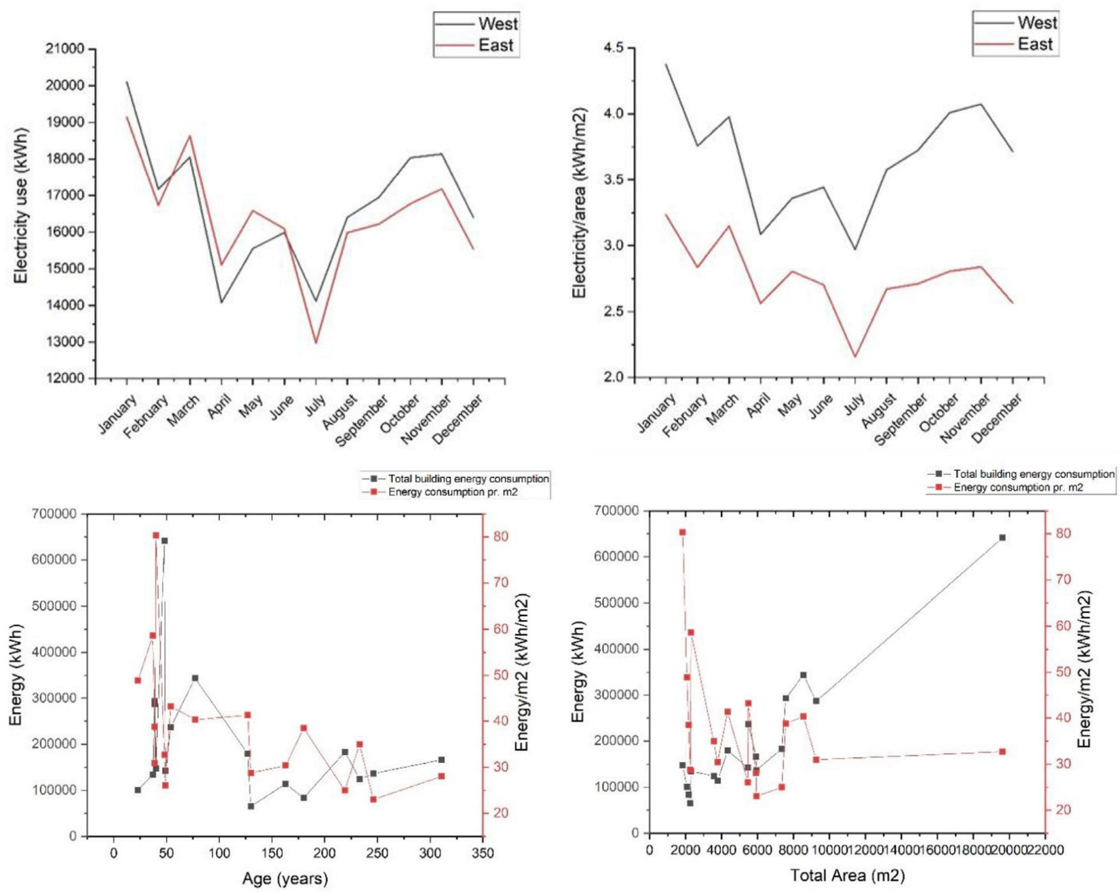

Fig. 7. Building electricity-consumption data. Top left: total electricity use. Top right: electricity use per m^2. Bottom left: electricity use by building age (years). Bottom right: electricity use by total area (m^2).

electricity consumption are found in the daily grid analysis section 4.4 of the SI.

The noticeable difference between weekend and weekdays in the daily data resolution, coupled with energy grid data of a corresponding resolution, may prove to be an effective data-resolution compromise. The observed trends are apparent for all buildings: they all have substantially higher electricity usage on weekdays, followed by drops over the weekend and on holidays.

The impacts induced per kWh do not follow the same trend as the consumption. While there are falls in the average induced impact per kWh throughout a week, electricity consumption and observable impacts peak on weekdays.

Although daily data resolution is not as detailed as hourly resolution, the fact that there are significant differences between the individual days, in terms of both consumption and induced impacts, stresses that daily data resolution still reveals factors that are not observable at lower data resolutions.

With daily data resolutions, the average impact potentials are again

Table 2
Total impact potentials results per m^2 for all buildings for the five chosen midpoint categories and from an hourly grid resolution.

Building	Marine eutrophication	Terrestrial acidification	Photochemical oxidant formation	Climate change	Ozone depletion
W1	3,00E-03	4,82E-02	3,27E-02	1,21E+01	1,63E-06
W3	2,49E-03	3,99E-02	2,71E-02	1,01E+01	1,35E-06
W4	1,54E-03	2,49E-02	1,69E-02	6,27E+00	8,37E-07
W5	2,00E-03	3,10E-02	2,11E-02	7,97E+00	1,05E-06
W6	4,15E-03	6,43E-02	4,37E-02	1,65E+01	2,19E-06
W7	1,99E-03	3,18E-02	2,16E-02	8,01E+00	1,08E-06
W8	1,67E-03	2,67E-02	1,81E-02	6,71E+00	9,03E-07
W9	1,50E-03	2,46E-02	1,67E-02	6,11E+00	8,27E-07
E1	2,03E-03	3,69E-02	2,32E-02	8,97E+00	1,14E-06
E2	1,46E-03	2,67E-02	1,67E-02	6,45E+00	8,25E-07
E3	1,94E-03	3,50E-02	2,20E-02	8,57E+00	1,09E-06
E4	1,43E-03	2,64E-02	1,66E-02	6,35E+00	8,16E-07
E5	1,66E-03	3,07E-02	1,93E-02	7,42E+00	9,48E-07
E6	1,33E-03	2,43E-02	1,52E-02	5,90E+00	7,50E-07
E7	1,90E-03	3,47E-02	2,18E-02	8,44E+00	1,07E-06
E8	1,19E-03	2,21E-02	1,38E-02	5,32E+00	6,80E-07
E9	1,06E-03	1,93E-02	1,21E-02	4,70E+00	5,99E-07
Unit	(kg N eq)/m^2	(kg SO_2 eq)/m^2	(kg NMVOC)/m^2	(kg CO_2 eq)/m^2	(kg CFC-11 eq)/m^2

higher for the buildings in western Denmark: on average 34% at both the midpoint and endpoint levels.

3.3.3. Monthly data resolutions

Monthly data resolutions address the changes that occur over the scale of one month and can still reflect the aggregated differences throughout the year, but on a monthly basis.

Electricity usage analyses based on monthly data resolutions are similar to the impacts obtained from applying hourly and daily data resolutions. They show once again that electricity consumption by the western buildings induces greater impacts than consumption by the eastern buildings. The results for the western buildings are on average 35% higher on the midpoint level and 32% higher on the endpoint level. There is obviously a direct correlation between electricity demand and the induced impacts, since the western buildings on average perform worse than their eastern counterparts. Since data regarding specific building functions and occupancy rates were not available at the time of this study, it has not proved possible to identify the cause of these patterns of energy efficiency.

3.3.4. Reference results

The reference results give the environmental performance of the buildings, calculated using the reference procedure in the ecoinvent 3.3 database.

Ecoinvent's system modelling is non-dynamic, as it does not take into account the temporal variations in the grid data or electricity consumption data. Application of the ecoinvent data framework method entails invariant impact results for every kWh produced throughout the year and therefore does not take into account the variation in the electricity consumption of the different buildings at different time intervals (hourly/daily/monthly).

Since the reference impact potentials per kWh for basic comparison are the same all year long, the differences in impacts between the eastern and western buildings are directly correlated with the energy results per m^2, which are 33.4% higher on average for western buildings.

3.3.5. Comparison

The differences in impact results per m^2 between the eastern and western buildings change to only a minor degree when we change the energy data resolution and base the calculation primarily on the consumption/m^2 of each building.

The value of the various data resolutions only becomes apparent when comparing the individual buildings and the variation in impacts resulting from the different data resolutions.

Since the energy data resolutions change in the comparisons, while building size, location and total energy consumption remain constant, any deviation in the environmental impact potential result solely from the changes in data resolution.

3.4. Midpoints

The difference ratios in terms of induced impacts observed among the different data resolutions stress that the hourly and daily data resolution levels, as seen in section 4.4.3 of the SI, only yield minor differences. Table 3 presents the differences across all impact categories when the hourly resolution is compared to the other grids. The difference in induced impacts for hourly/daily resolutions across all impact categories is on average $< 3\%$, with the daily data resolution resulting in slightly higher impacts. The exception is building W4, for which the hourly data resolution impacts are 9.8% higher. Building W4 is equipped with solar panels that produce a significant amount of its electricity demand, as a result of which the higher data resolution influences the results for W4 more than it does for the other buildings. When comparing the hourly to the monthly data resolutions, the variations in the results become more distinct. The differences in average impacts are up to 7.8% higher when using monthly instead of hourly data resolutions.

Table 3
Average total differences across all impact categories when compared to the impact potentials obtained by applying the hourly data resolution.

Building	Hourly/daily resolutions	Hourly/monthly resolutions	Hourly/reference resolutions
W1	1.8%	5.4%	158.8%
W3	2.9%	6.1%	165.6%
W4	9.8%	7.8%	134.3%
W5	2.3%	3.7%	158.7%
W6	1.8%	3.7%	157.8%
W7	1.6%	5.0%	159.4%
W8	1.6%	5.2%	160.3%
W9	1.9%	6.3%	160.0%
E1	1.3%	3.5%	187.9%
E2	1.4%	3.8%	187.2%
E3	1.5%	2.9%	187.1%
E4	1.3%	4.2%	188.5%
E5	1.5%	4.0%	188.2%
E6	1.4%	3.2%	186.5%
E7	1.3%	3.6%	187.4%
E8	1.3%	3.9%	186.9%
E9	1.5%	3.9%	190.9%

The results obtained by comparing the hourly data resolution system with the reference data resolutions reveals more substantial differences than the other comparisons. The impacts obtained by applying the reference data resolutions are significantly higher and range between 134.3 and 190.9%. However, this difference is amplified by the four specific categories where the difference exceeds 400%. Ignoring these four categories results in average differences of between 40% and 71%, which the authors consider more reasonable.

The deviations presented in Table 4 show that, except for the occupation of agricultural land, all induced impacts are higher (in some cases over 600%) when using the reference data resolutions. In particular, four specific categories show extreme differences between the two resolutions: ionizing radiation, freshwater ecotoxicity, marine ecotoxicity and water depletion.

These extreme variations are most likely due to certain energy production processes that are present or represented in the reference data resolutions but not present to the same extent in the hourly calculated energy grid compositions. We estimate that this pattern is caused by an over-represented reliance on imported electricity and coal- or waste-based electricity in the reference data resolutions.

Table 4
Deviations in midpoint impact results per m^2 averaged for all buildings, between reference data and hourly data resolution, for western and eastern Denmark.

Reference vs. hourly resolution	West	East
Fossil depletion	77.8%	84.1%
Marine eutrophication	34.1%	47.3%
Terrestrial acidification	56.0%	45.2%
Ionizing radiation	403.6%	541.6%
Freshwater ecotoxicity	469.4%	664.4%
Photochemical oxidant formation	32.4%	33.3%
Terrestrial ecotoxicity	101.9%	118.8%
Marine ecotoxicity	435.3%	609.1%
Climate Change	84.6%	82.6%
Particulate matter formation	48.7%	41.6%
Human toxicity	50.5%	73.6%
Metal depletion	120.9%	188.7%
Natural land transformation	84.5%	83.1%
Urban land occupation	15.7%	1.8%
Water depletion	568.9%	437.2%
Freshwater eutrophication	21.9%	49.4%
Ozone depletion	82.9%	87.3%
Agricultural land occupation	−24.9%	−36.5%

Occupation of agricultural land yields higher impacts when using the hourly data resolutions, most likely due to the amounts of biomass-based electricity being under-estimated when using reference data resolutions.

The differences between reference system and hourly data system already become evident in the calculation of the induced impacts per unit of electricity production: the reference system induces significantly higher impacts per kWh for all impact categories except the occupation of agricultural land. However, these differences in impact are amplified when coupled with the data for building electricity consumption, where the difference in data resolution amplifies the already substantial differences, this being observed for most impact categories. For instance, the difference when comparing hourly and reference data resolutions in terms of impacts per kWh produced on average amounts to 50.5% (west) and 73.6% (east) for human toxicity. However, these differences, which are expressed in terms of impacts per unit of energy consumed, amplify the differences to 58% (west) and 82% (east). This shows that the variation has its origin in the calculations of power grid composition, and that the difference is further amplified by the difference in data resolution, most likely because of the far from average grid composition observed during peak consumption in the seventeen buildings.

3.5. Endpoints

The endpoint scores for all buildings are presented as impact potentials per m^2 in section 4 in the SI. As with the midpoint impact potentials, comparison of the results becomes clearer when using the relative comparisons based on percentage values.

Contrary to the midpoint impact comparison of hourly, daily and monthly data resolutions, the endpoint scores are consistently higher for the hourly resolutions across all categories and for all buildings. Once again, building W4 is an outlier due to its solar panels. For the remaining buildings, the hourly/daily comparisons show differences of up to 5%, and of over 6% for the hourly/monthly comparison.

Comparison between the hourly and reference data resolutions yields differences in ecosystem impacts that are considerably lower than for human health and resources. Depending on the building, the impact potentials are either higher or lower. The results differ on average between 5% (lower) and 8% (higher). However, the impact potentials for the other two endpoint categories are substantially higher for hourly data when compared with the reference system: on average, 71% higher for human health and over 81% for resources. As with the midpoint impact potentials, the reference data resolutions yield notably higher endpoint scores when compared to any of the results from the other systems that apply dynamic data resolutions.

In terms of the grid composition specific impacts, the data resolution dependency observed for the mid-points are repeated by the endpoints. The agricultural land occupation at the midpoint level is regarded as an outlier that is lower for the reference system. Also, the ecosystem impact endpoint is the category least affected by the application of dynamic grid data. Both impacts and impact groups are to some degree dependent on the flows connected to the use of biomass in electricity production. The effect is therefore apparent for both midpoint and endpoint scores (see Table 5).

4. Discussion

4.1. Reference data resolution

One of the focus points of this study is the comparison between the induced impact per kWh consumed when calculated by relying on the reference process found in the ecoinvent database and that found the measured electricity production data provided by Energinet for electricity and natural gas.

The two ways of calculating energy consumption-induced impacts differ in two major ways: first, in the energy sources covered by the reference data set that are absent when calculating the impacts from the observed and measured data; and secondly, in the temporal dynamics of the data.

While the major contributing form of electricity production is the same both in this study and in the database, that in the ecoinvent database: *market for electricity, low voltage | DK*, includes several inputs that are not present in the electricity production recorded in 2017, such as hydro-power, or the inclusion of the transmission network. This is a major source of disparity between the two methods of calculation, without it being clear which is the most accurate.

The second major difference is in the respective timeframes covered by the two methods. The ecoinvent reference database from openLCA was more than six years old (from 2012) at the time of our study, that is, five years older than the energy data used in the study (from 2017). Given the ways in which Denmark's energy grid has developed in the past six years in shifting towards more sustainable electricity production, the age of the reference process found in the ecoinvent database justifies the results obtained by using dynamic data.

Furthermore, the reference process for electricity production does not take into account the variations in the electricity grid that occur throughout the year. As the results from the energy grid indicate, there are notable changes in the impacts per kWh consumed depending on the time of year the electricity is produced, and the lack of temporal dynamics in the reference process is a major source of inaccuracy.

4.2. The complexity of energy data for buildings

From the analysis of the data for building energy consumption, it has become apparent that the key component when comparing the environmental performance of the buildings is the performance indicator "energy consumption/building area". The differences in their impact potentials are directly correlated with the difference in energy consumption/building area.

A more accurate comparison between the buildings would require more complex data on them with regard to their functions and occupancy rates. The functions of each building vary, as can be observed from the daily electricity consumption data, where some buildings have a clear reduction during holidays, while others do not.

While our study focuses on the importance of temporal variations in energy consumption data for office buildings in Denmark, Roux et al. (2016) have conducted a similar study of a single-family house in France. Their results show that the impacts could differ by up to 40% depending on the temporal variations in the data. Our findings, combined with these earlier findings by Roux et al., highlight the necessity of increased temporal variation being incorporated into LCA, but they also emphasise that the results of dynamic LCA are context-dependent. This means that parameters such as building location (country/region), building functionality (residential/non-residential), occupancy rate (area/person) and energy composition should be addressed in any dynamic LCA approach.

Among the factors that contribute to the demand for energy and that play a role in the EBP of office buildings are the number of occupants, the hours of work and activities that take place outside the regular business hours, but these factors are not reflected in our analysis, which focuses solely on gross energy consumption. Should such temporal data become more available for future studies, more suitable comparisons of the environmental performances of these buildings might be possible, especially since some trends in comparisons, such as building age – as illustrated in this study – proved inconclusive. Appropriate comparisons might be made of environmental performance per occupant of a given building at any given time, or of the performance both during and outside of business hours, to determine which office buildings could be optimized with regard to their baseline operational energy consumption.

Table 5
Total endpoint score comparison between the hourly grid resolutions and the daily/monthly grid resolutions, as well as the reference grid, for all buildings. Differences displayed in percentages.

Building	Hourly/daily resolutions				Hourly/monthly resolutions				Hourly/reference resolutions			
	Ecosystems	Human health	Resources	Average	Ecosystems	Human health	Resources	Average	Ecosystems	Human health	Resources	Average
W1	−5.2%	−4.9%	−2.7%	−4.3%	−6.7%	−1.9%	0.1%	−2.8%	5.8%	72.3%	79.3%	52.5%
W3	−3.6%	−2.1%	−0.2%	−2.0%	−4.5%	0.2%	2.0%	−0.8%	4.9%	72.5%	79.4%	52.3%
W4	−15.6%	−13.8%	−12.4%	−13.9%	−16.1%	−12.5%	−11.1%	−13.2%	−10.6%	48.4%	54.5%	30.8%
W5	−3.3%	−2.8%	−0.8%	−2.3%	−4.2%	−2.1%	−0.1%	−2.1%	7.4%	71.1%	78.1%	52.2%
W6	−3.6%	−3.5%	−1.4%	−2.8%	−4.7%	−2.3%	−0.3%	−2.4%	8.3%	72.1%	79.0%	53.1%
W7	−4.8%	−4.4%	−2.3%	−3.8%	−6.0%	−1.7%	0.3%	−2.5%	5.7%	72.1%	79.1%	52.3%
W8	−4.8%	−4.3%	−2.2%	−3.7%	−6.0%	−1.5%	0.4%	−2.4%	6.5%	73.3%	80.3%	53.4%
W9	−5.1%	−3.5%	−1.6%	−3.4%	−6.6%	−0.8%	1.0%	−2.1%	2.4%	70.3%	77.3%	50.0%
E1	−3.0%	−3.8%	−2.4%	−3.0%	−3.6%	−2.2%	−0.7%	−2.2%	−1.7%	73.9%	87.9%	53.4%
E2	−3.0%	−3.8%	−2.4%	−3.0%	−4.7%	−2.6%	−1.1%	−2.8%	−2.2%	73.7%	87.7%	53.1%
E3	−2.6%	−3.5%	−2.2%	−2.8%	−2.9%	−2.3%	−0.9%	−2.0%	−1.2%	73.8%	87.7%	53.5%
E4	−2.9%	−4.0%	−2.7%	−3.2%	−4.2%	−1.9%	−0.4%	−2.1%	−3.5%	73.0%	87.0%	52.2%
E5	−3.0%	−3.6%	−2.2%	−2.9%	−3.8%	−1.8%	−0.4%	−2.0%	−4.7%	70.8%	84.8%	50.3%
E6	−2.8%	−3.6%	−2.2%	−2.9%	−3.4%	−2.3%	−0.9%	−2.2%	−3.1%	71.9%	85.8%	51.5%
E7	−3.1%	−3.9%	−2.5%	−3.2%	−3.9%	−2.3%	−0.8%	−2.4%	−2.7%	72.8%	86.8%	52.3%
E8	−2.9%	−3.8%	−2.4%	−3.0%	−3.8%	−1.9%	−0.5%	−2.1%	−5.3%	69.9%	83.9%	49.5%
E9	−2.8%	−3.6%	−2.1%	−2.8%	−3.5%	−1.8%	−0.3%	−1.9%	0.2%	77.1%	91.2%	56.2%

5. Conclusion

The composition of the Danish electricity grid comprises numerous sources whose relative contributions to the sum change over time. Assessing these dynamic data patterns and their implications for the environment in this study has proved to have a great influence on the impact potentials of electricity production, as well as the environmental performance of the buildings supplied by this grid.

The energy grid analysis shows that the data resolution (month/day/hour) for electricity production is important, as it directly influences the environmental impacts arising from electricity production. Our study also shows that, even without changing the building area or total electricity demand, the data resolutions changed the overall results. However, the differences between the results were not always substantial enough to justify the increased volumes of data and the time required to perform highly detailed analyses. For the midpoint characterization, the daily resolutions provided results very similar to those of the hourly resolutions, and, given the fact that the former require 24 times more data points than the daily data, the daily data resolutions are the most reasonable solution to recommend. The endpoint scores proved to be another story, as every increment in data resolution provided significant changes in results. As such the choice of data resolution will impact on the results for any increment used.

In almost all scenarios, the impact potentials calculated from the electricity production data collected differ greatly from the impact potentials calculated from the ecoinvent database. Nonetheless, the applied reference process is based on data that are five years older than the research data used in the study, while the Danish electricity grid data shows that the composition of the energy grid has changed greatly over the same period. The results show substantial deviation across all impact categories between the different electricity grids used, while methodological choices may to a degree influence this deviation. The analysis of the yearly development of the Danish electric grid showed substantial changes in the composition of the grid, which the reference process does not account for.

The analysis of the composition of the electric grid throughout the year shows that renewable energy sources dramatically reduce the environmental impact per kWh, but that they are still unreliable in respect of their contributions to the grid. Given the results of this study, a dynamic inventory modelling approach would always be recommended, but in cases where sufficient quantities and quality of data are not assured, a compromise could be achieved by creating building type-specific electrical grid processes in databases such as ecoinvent. These processes could be representative of different building functions such as residential, commercial or other and could correspond to a grid and electricity consumption profile that portrays more accurately the impacts of the grid during the operating and non-operating hours of various building types.

The dynamic high-resolution data are obviously significantly more accurate and have proved to be greatly influential on environmental performance during the buildings' use stages. The future development of dynamic electrical grid modelling practices will provide real-time assessments of the energy performance of buildings once such data become available in real time. This will allow buildings to become reactive in terms of their electricity consumption by allocating less essential electricity-consuming processes to times when the environmental footprint of the grid composition is more favourable.

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Appendix B: Co-author statements

Declarations of co-authorship at DTU

If a PhD thesis contains articles (i.e. published journal and conference articles, unpublished manuscripts, chapters, etc.) written in collaboration with other researchers, a co-author statement verifying the PhD student's contribution to each article should be made.

If an article is written in collaboration with three or less researchers (including the PhD student), all researchers must sign the statement. However, if an article has more than three authors the statement may be signed by a representative sample, cf. article 12, section 4 and 5 of the Ministerial Order No. 1039, 27 August 2013. A representative sample consists of minimum three authors, which is comprised of the first author, the corresponding author, the senior author, and 1-2 authors (preferably international/non-supervisor authors).

DTU has implemented the Danish Code of Conduct for Research Integrity, which states the following regarding attribution of authorship:

"Attribution of authorship should in general be based on criteria a-d adopted from the Vancouver guidelines[1], and all individuals who meet these criteria should be recognized as authors:

a. Substantial contributions to the conception or design of the work, or the acquisition, analysis, or interpretation of data for the work, *and*
b. drafting the work or revising it critically for important intellectual content, *and*
c. final approval of the version to be published, *and*
d. agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved."[2]

For more information regarding definition of co-authorship and examples of authorship conflicts, we refer to DTU Code of Conduct for Research Integrity (pp. 19-22).

By signing this declaration, co-authors permit the PhD student to reuse whole or parts of co-authored articles in their PhD thesis, under the condition that co-authors are acknowledged in connection with the reused text or figure.

It is **important** to note that it is the responsibility of the PhD student to obtain permission from the publisher to use the article in the PhD thesis[3]

[1] International Committee of Medical Journal Editors – Recommendations for the Conduct, Reporting, Editing, and Publication of Scholarly Work in Medical Journals, updated December 2016
[2] DTU Code of Conduct for Research Integrity (E-book p. 19)
[3] Many journals will allow you to use only the post-print version of your article, meaning the accepted version of the article, without the publisher's final formatting. In the event that your article is submitted, but still under review, you should of course use the latest submitted version of your article in your thesis. Always remember to check your publisher's guidelines on reuse

Technical University of Denmark

Title of article	
Indicators for quantifying environmental building performance: A systematic literature review	
Journal/conference	
Journal of Building Engineering	
Author(s)	
Esmir Maslesa, Per Anker Jensen, Morten Birkved	
Name (capital letters) and signature of PhD student	
ESMIR MASLESA	
PhD student's date of birth	
28-08-1984	
Declaration of the PhD student's contribution	
For each type of work, please specify below the contribution as appropriate	

	Minor contribution to the work *(please specify)*	**Substantial contribution to the work** *(please specify)*
Formulation of the conceptual framework and/or planning of the design of the study including scientific questions		• Defining research topic • Defining research method
Carrying out of experiments/data collection and analysis/interpretation of results		• Systematic literature review • Database search • Data (articles) analysis – two iterations • Interpretation of results
Writing of the article/revising the manuscript for intellectual content		• Writing the article • Article submission • Article revision

of published articles. Most journals, unless open access, have an embargo period on published articles, meaning that within this period you cannot freely use the article. Check your publisher's rules on this issue.

Technical University of Denmark

Title of article
Indicators for quantifying environmental building performance: A systematic literature review
Journal/conference
Journal of Building Engineering
Author(s)
Esmir Maslesa, Per Anker Jensen, Morten Birkved
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Signatures

Date	**Name**	**Title**	**Signature**
29-01-2019	Per Anker Jensen	Associate Professor	
24-01-2019	Morten Birkved	Professor, MSO	

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Technical University of Denmark

DTU

Title of article
10 questions concerning sustainable building renovation
Journal/conference
Building and Environment
Author(s)
Per Anker Jensen, Esmir Maslesa, Jakob Brinkø Berg, Christian Thuesen
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Declaration of the PhD student's contribution
For each type of work, please specify below the contribution as appropriate

	Minor contribution to the work *(please specify)*	**Substantial contribution to the work** *(please specify)*
Formulation of the conceptual framework and/or planning of the design of the study including scientific questions		• Theoretical framing
Carrying out of experiments/data collection and analysis/interpretation of results		• Section 2.7 • Section 2.8 • Discussion
Writing of the article/revising the manuscript for intellectual content	Writing the article	• Article revisions

Technical University of Denmark

Title of article
10 questions concerning sustainable building renovation
Journal/conference
Building and Environment
Author(s)
Per Anker Jensen, Esmir Maslesa, Jakob Brinkø Berg, Christian Thuesen
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Signatures

Date	Name	Title	Signature
29-01-2019	Per Anker Jensen	Associate Professor	
28-01-2019	Jakob Brinkø Berg	PhD fellow	
xx-xx-xxxx	Christian Thuesen	Associate Professor	Unavailable. The statement is signed by a representative sample, cf. article 12, section 4 and 5 of the Ministerial Order No. 1039, 27 August 2013.

Please note that by signing this declaration, co-authors permit the PhD student to reuse whole or parts of co-authored articles in their PhD thesis, under the condition that co-authors are acknowledged in connection with the reused text or figure.

Technical University of Denmark

Title of article
The implementation impacts of IT systems on energy management in real estate organisations
Journal/conference
European Facilities Management Conference (EFMC) 2018, Sofia, Bulgaria
Author(s)
Esmir Maslesa, Per Anker Jensen
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Declaration of the PhD student's contribution
For each type of work, please specify below the contribution as appropriate

	Minor contribution to the work *(please specify)*	**Substantial contribution to the work** *(please specify)*
Formulation of the conceptual framework and/or planning of the design of the study including scientific questions		• Theoretical framing • Research method • Research criteria
Carrying out of experiments/data collection and analysis/interpretation of results		• Data collection • Data analysis • Model development
Writing of the article/revising the manuscript for intellectual content		• Article writing • Article submisison • Article revision

Technical University of Denmark

DTU

Title of article

The implementation impacts of IT systems on energy management in real estate organisations

Journal/conference

European Facilities Management Conference (EFMC) 2018, Sofia, Bulgaria

Author(s)

Esmir Maslesa, Per Anker Jensen

Name (capital letters) and signature of PhD student

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PhD student's date of birth

28-08-1984

Signatures

Date	Name	Title	Signature
29-01-2019	Per Anker Jensen	Associate Professor	Per Anker Jensen

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Technical University of Denmark

DTU

Title of article
Drivers for IWMS implementation in real estate management
Journal/conference
Journal of Corporate Real Estate
Author(s)
Esmir Maslesa, Per Anker Jensen
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Declaration of the PhD student's contribution

For each type of work, please specify below the contribution as appropriate

	Minor contribution to the work *(please specify)*	**Substantial contribution to the work** *(please specify)*
Formulation of the conceptual framework and/or planning of the design of the study including scientific questions		• Theoretical framing • Research method • Research criteria
Carrying out of experiments/data collection and analysis/interpretation of results		• Data collection • Data analysis • IWMS defintion • Drivers for IWMS
Writing of the article/revising the manuscript for intellectual content		• Article writing • Article submisison • Article revision

Title of article
Drivers for IWMS implementation in real estate management
Journal/conference
Journal of Corporate Real Estate
Author(s)
Esmir Maslesa, Per Anker Jensen
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984

Signatures

Date	**Name**	**Title**	**Signature**
29-01-2019	Per Anker Jensen	Associate Professor	

Please note that by signing this declaration, co-authors permit the PhD student to reuse whole or parts of co-authored articles in their PhD thesis, under the condition that co-authors are acknowledged in connection with the reused text or figure.

Technical University of Denmark

Title of article
Managing environmental building performance through IT systems
Journal/conference
Facilities
Author(s)
Esmir Maslesa, Per Anker Jensen
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Declaration of the PhD student's contribution
For each type of work, please specify below the contribution as appropriate

	Minor contribution to the work *(please specify)*	**Substantial contribution to the work** *(please specify)*
Formulation of the conceptual framework and/or planning of the design of the study including scientific questions		• Theoretical framing • Research method • Research criteria
Carrying out of experiments/data collection and analysis/interpretation of results		• Data collection • Cross-case analysis • EMS/BMS models
Writing of the article/revising the manuscript for intellectual content		• Article writing • Article submisison • Article revision

Technical University of Denmark

DTU

Title of article
Managing environmental building performance through IT systems
Journal/conference
Facilities
Author(s)
Esmir Maslesa, Per Anker Jensen
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PhD student's date of birth
28-08-1984
Signatures

Date	Name	Title	Signature
29-01-2019	Per Anker Jensen	Associate Professor	Per Anker Jensen

Please note that by signing this declaration, co-authors permit the PhD student to reuse whole or parts of co-authored articles in their PhD thesis, under the condition that co-authors are acknowledged in connection with the reused text or figure.

Technical University of Denmark DTU

Title of article
Environmental performance assessment of the use stage of buildings using dynamic high-resolution energy consumption and data on grid composition
Journal/conference
Building and Environment
Author(s)
Asger Alexander Wendt Karl, Esmir Maslesa, Morten Birkved
Name (capital letters) and signature of PhD student
ESMIR MASLESA
PhD student's date of birth
28-08-1984
Declaration of the PhD student's contribution
For each type of work, please specify below the contribution as appropriate

	Minor contribution to the work *(please specify)*	**Substantial contribution to the work** *(please specify)*
Formulation of the conceptual framework and/or planning of the design of the study including scientific questions		• Formulating research topic • Defining research method and criteria • Theoretical framing • Co-supervising master student
Carrying out of experiments/data collection and analysis/interpretation of results		• Data collection from BYGST • Interpretation of results
Writing of the article/revising the manuscript for intellectual content	Writing the article	• Article revisions • Article submissions

Technical University of Denmark

Title of article
Environmental performance assessment of the use stage of buildings using dynamic high-resolution energy consumption and data on grid composition
Journal/conference
Building and Environment
Author(s)
Asger Alexander Wendt Karl, Esmir Maslesa, Morten Birkved
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Date	**Name**	**Title**	**Signature**
3.12.2018	Asger Alexander Wendt Karl	Master student	
3.12.2018	Morten Birkved	Professor	

Please note that by signing this declaration, co-authors permit the PhD student to reuse whole or parts of co-authored articles in their PhD thesis, under the condition that co-authors are acknowledged in connection with the reused text or figure.

Appendix C: Publication list

Complete publication list in chronological order (most recent publications first)

2019

Improving the environmental performance of buildings.
Maslesa, Esmir.
In: Facilities Management Models, Methods and Tools: Research Results for Practice
Polyteknisk Forlag, book part B.II, chapter 12, p. XX-XX (forthcoming)

Managing environmental building performance through IT systems. ***(P5)***
Maslesa, Esmir; Jensen, Per Anker. (2019b)
Facilities (submitted)

Drivers for IWMS implementation in real estate management. ***(P4)***
Maslesa, Esmir; Jensen, Per Anker. (2019a)
Journal of Corporate Real Estate, Vol. XX, 2019, p. XX-XX (accepted/in press)

Electricity production and consumption data from Danish power grid and governmental office buildings.
Karl, Asger Alexander Wendt; Maslesa, Esmir; Birkved, Morten.
Data in Brief, reference: DIB3684. https://doi.org/10.1016/j.dib.2019.01.032

Environmental performance assessment of the use stage of buildings using dynamic high-resolution energy consumption and data on grid composition. ***(P6)***
Karl, Asger Alexander Wendt; Maslesa, Esmir; Birkved, Morten.
Building and Environment, Vol. 147, 2019, p. 97-107.

- 2018

Sustainable Building Renovation: Proposals for a Research Agenda
Jensen, Per Anker; Maslesa, Esmir; Berg, Jakob Brinkø.
Sustainability 2018, 10, 4677

The role of Energy Management System for heating consumption in office buildings: a case study of the Danish building and property agency.
Maslesa, Esmir; Jensen, Per Anker; Jimenez-Bescos, Carlos
Abstract presented at 4TH International Conference on Smart Energy Systems and 4TH Generation District Heating, 13-14 November 2018, Aalborg, Denmark. Book of Abstracts, p. 216.

10 questions concerning sustainable building renovation. ***(P2)***
Jensen, Per Anker; Maslesa, Esmir; Berg, Jakob Brinkø; Thuesen, Christian.
Building and Environment, Vol. 143, 2018, p. 130-137.

The implementation impacts of IT systems on energy management in real estate organisations.
(P3) Maslesa, Esmir; Jensen, Per Anker.
Research paper for EFMC 2018, European Facilities Management Conference, Sofia, Bulgaria.

2018 -

Indicators for quantifying environmental building performance: A systematic literature review. ***(P1)***
Maslesa, Esmir; Jensen, Per Anker; Birkved, Morten.
Journal of Building Engineering, Vol. 19, 2018, p. 552-560.

Forbedring af miljømæssig bygningsperformance.
Maslesa, Esmir.
Book chapter in: CFM forskning igennem 10 år. De vigtigste modeller, metoder og værktøjer
Polyteknisk Forlag, chapter 12, p. 81-85.

2017

Environmental indicators for non-residential buildings: when, what, and how to measure?
Maslesa, Esmir; Nielsen, Susanne Balslev; Birkved, Morten; Hultén, Jannik.
Research paper for EuroFM's 16th Research Symposium at EFMC2017, Madrid, Spain.
Polyteknisk Boghandel og Forlag, 2017. p. 8-20.

2016

Dynamic optimization of building performance: use of real-time building data for improving facilities management.
Maslesa, Esmir; Nielsen, Susanne Balslev; Birkved, Morten; Hultén, Jannik.
Abstract for Sustain-ATV Conference 2016, DTU, Kgs. Lyngby, Denmark.

Organising Sustainable Transition: Understanding the Product, Project and Service Domain of the Built Environment.
Thuesen, Christian; Koch-Ørvad, Nina; Maslesa, Esmir.
Research paper in proceedings of the 32nd Annual ARCOM Conference, Manchester, UK.
Association of Researchers in Construction Management, 2016.